SUN-BURNED:
SPACE WEATHER'S IMPACT ON US NATIONAL SECURITY

BY

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DISCLAIMER

The conclusions and opinions expressed in this document are those of the author. They do not reflect the official position of the US Government, Department of Defense, the United States Air Force, or Air University.

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ABSTRACT

The projected period of heightened solar activity in 2013 presents an opportune occasion to examine the ever-increasing vulnerability of US national security and its Department of Defense to space weather. This vulnerability exists for three principal reasons: 1) a massive US space-based infrastructure; 2) an almost exclusive reliance on an aging and stressed continental US power grid; and 3) a direct dependence upon a US economy adapted to the conveniences of space and uninterrupted power.

Aimed mainly at national security policy makers and military strategists, this work endeavors to initiate and inform a substantive dialogue on America's preparation for, and response to, a major solar event that would severely degrade core national security capabilities, such as military operations. Significant risk to the Defense Department exists from powerful events that could impact its space-based infrastructure and even the terrestrial power grid. Given this ever-present and increasing risk, this thesis advocates that the United States raise the issue of space weather and its impacts to the level of a national security threat. With the current solar cycle already in its peak phase and the next projected solar maximum in 11 years, the government has a relatively small window to make policy decisions that ensure the nation and Defense Department are prepared.

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Chapter 1

Introduction

One of the problems with extreme events is that prior to their occurrence, their perceived risk is effectively zero, yet following it, the risk rises to nearly 100%.
Predictive Scientist, Dr. Pete Riley, 2012

The projected period of heightened solar activity in 2013 presents an opportune occasion to examine the ever-increasing vulnerability of the United States of America to space weather. While space weather effects do not discriminate, the US national security enterprise, and in particular its cornerstone, the Department of Defense, finds itself critically vulnerable to space weather impacts because of three principal factors: 1) a massive US space-based infrastructure; 2) an almost exclusive reliance on an aging and stressed continental US power grid; and 3) a direct dependence upon a US economy adapted to the conveniences of space and uninterrupted power.

Aimed mainly at national security policy makers and military strategists, this thesis asserts that the US security apparatus is not adequately prepared to continue operations during and after a major space weather event. As such, this work endeavors to initiate and inform a substantive dialogue on America's preparation for, and response to, a major solar event that would severely degrade core national security capabilities, such as military operations. Lastly, this thesis will investigate various mechanisms for mitigating space weather impacts to America's national security and will offer recommendations for consideration by policy makers.

Could it happen?

Imagine a day with no ability to communicate over long distances—no technological means available to transmit beyond visual or aural ranges. An unknown force renders inoperable the most advanced communications systems. Overhead, heavy cables usually relegated to background noise as a low drone now buzz excitedly and flare occasionally in bright discharges of blue light. An abnormally intense electrical current ignites small fires in ground stations as perplexed operators struggle to understand the commotion around them. With the main medium for disseminating flash news across the country malfunctioning, even the few scientists who hold only disparate clues to the remarkable events cannot collaborate.

Sensor needles pulse wildly all over the world in an attempt to record extreme readings beyond instrument design capacities. Isolated communities of people, already desperate from the loss of communications, verge on hysteria as they stand awestruck while gazing skyward at a vibrant panoply of color. So great is the illumination interposed upon the night sky that it rivals the Moon when in full reflection. Incredulous government officials at all levels must fend for themselves as they try to manage this overwhelming situation with no real sense of the obstacles they face.

While trying to sort through the portrayed chaos above, a few foundational questions emerge. First, what physical phenomenon would seemingly target high-technology systems with such ferocity? Second, what would trigger a catastrophic event like this? Third, and perhaps most relevant, could such a calamity really ever come to pass? To find the answers to these questions and more, the search must begin not here on Earth, but with the massive fusion reactor known as the Sun, for a solar eruption that enveloped the Earth would generate these wide-ranging impacts and would have the potential to disrupt nearly all modern technology. If revelation of this origin leads to dismissive

thoughts of science fiction or the realm of fantasy, consider carefully that not only could this happen, it already has…in 1859.[1]

Overview

Before the actual events from 150 years ago are detailed in the next chapter's historical survey, this introductory chapter continues by presenting some contextual material in order to provide the necessary foundation for the argument. A few basic definitions and examples, fundamental to any composition, start bounding the argument by delineating the space weather domain and its constituent elements. Successive sections then review the space weather literature, describe the methodology used to reach the thesis conclusion, and state the limitations of this work before summarizing the chapter with a short closing.

Chapter 2 outlines a few of the more noteworthy space weather events that affected the Earth in the past. Listing them in chronological order, the chapter starts with the unprecedented Carrington Event alluded to in the previous section and ends with the relatively recent Halloween storm of 2003. It then briefly looks at the current year, 2013, as the predicted solar maximum. Chapter 3 momentarily provides the supporting logic behind having selected the Department of Defense as the center of gravity for America's security. Chapter 4 delves into more detail on the specific impacts on national security by addressing the three principal Defense Department vulnerabilities to space weather listed in the opening. It then appraises the current US interagency approach to space weather through a deeper examination of a few constituent stakeholders. Finally, chapter 5 concludes the paper with a general policy recommendation and a few supportive actions that will enable that policy.

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[1] M. J. Carlowicz and R. E. Lopez, *Storms from the Sun: The Emerging Science of Space Weather* (Washington, DC: The Joseph Henry Press, 2002), 51-59.

Space Weather

The somewhat constraining Department of Defense characterization defines space weather as, "The conditions and phenomena in space and specifically in the near-Earth environment that may affect space assets or space operations."[2] The US government's National Space Weather Program submits a more inclusive definition: "Space weather refers to conditions on the Sun and in the space environment that can influence the performance and reliability of space-borne and ground-based technological systems, and can endanger human life or health."[3] To its detriment, the former definition appears to disregard the potential for very real and significant impacts to non-space related terrestrial systems such as power grids. To put it more succinctly and still remain inclusive, space weather encompasses all stellar phenomena found within the space environment that have the potential to cause hazardous effects.

For the Earth and its planetary neighbors, space weather emanates predominantly from their nearest star—the Sun. As a result, popular media will sometimes refer to "solar weather," which has its etymological root in the ancient Roman god for the Sun, *Sol*, and the subsequent Latin adjectival form, *solaris*.[4] It is important to note the two terms are not entirely synonymous, as "space weather" may include other phenomena, such as highly energetic cosmic rays from stars outside the Solar System. The terms are, however, sometimes used

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[2] Joint Publication 3-59, *Meteorological and Oceanographic Operations*, 7 December 2012, GL-5.

[3] Richard Fisher, "National Space Weather Program," National Aeronautics and Space Administration, http://www.nswp.gov/nswp_index.htm (accessed 18 October 2012).

[4] *Merriam-Webster's Collegiate Dictionary*, 11th ed., s.v. "solar."; Journals and other formal work on the subject generally refrain from using the term "solar weather," preferring the more scientifically proper "space weather." As this paper focuses on phenomena emanating from the Sun (see "Limitations" sub-section later in chapter), and because "solar weather" now resides in the general lexicon, I have periodically used the terms, space and solar, interchangeably with the full recognition that they are not wholly synonymous.

interchangeably and as such, both generally refer to observed weather from the Sun.

The weather analogy helps to make an intuitive connection between the general public and the different solar phenomena. Examples include the solar wind streaming continuously from the Sun in all directions and the geomagnetic storming during an excited state of the Earth's upper atmosphere. The familiar sounding "wind" and "storming" lead to an easy association with weather, yet not all events have such readily corresponding labels. Examples include two of the more ominous sounding phenomena, solar flares and coronal mass ejections. Lastly, the very appropriate moniker, meteor shower, may lead to its inclusion in a discussion on space weather, but the aforementioned definitions exclude interplanetary objects like asteroids and comets.

The Impact of Space Weather

Despite the use of a rather innocuous sounding analogy to atmospheric meteorology, space weather warrants close attention because of the impacts it can cause both in space and on the Earth. To produce an impact, a particular phenomenon must have some discernible effect on an object. The phenomenon's intensity does not always correlate directly with the significance of the impact. For example, a nominal solar wind, as measured by speed or density, relentlessly bombards a long-duration spacecraft with charged particles on a transit to Mars.[5] Although relatively weak, the cumulative effect of the wind-driven plasma could result in a significant impact if planners do not adequately account for constant the barrage of particles and take necessary precautions.[6] Alternatively, a strong solar flare could discharge a concentrated burst of x-rays in a spiraling trajectory that

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5 C. Zeitlin et al., "Measurements of Energetic Particle Radiation in Transit to Mars on the Mars Science Laboratory," *Science* 340, no. 6136 (2013): 1080-84.
6 J. W. Freeman, *Storms in Space* (New York: Cambridge University Press, 2001), 14-20.

sends it away from orbiting planets or manmade satellites. The lack of intercept would result in a negligible impact even if the flare served as a tool to forecast impending solar activity.

As will be shown in the next chapter, a historic space weather event produced very significant effects on near-Earth space, yet resulted in few impacts because neither man nor machine had ventured beyond the lower atmosphere. Similarly, the US bulk-power system did not then penetrate society as deeply as it does today, so impacts were limited. Some space weather impacts are relatively minor but affect a great many people at more frequent intervals. Two examples include marginal position errors in single frequency global positioning system receivers and seasonal interference to satellite television broadcasts.

As alluded to above, space agencies have had to account for the impacts of solar radiation on both manned and unmanned spacecraft since the advent of the space age. Shielding helps limit radiation exposure to critical satellite components as well as protect any organic tissue that may be aboard. Similarly, but to a much lesser extent, aircraft that fly high in the stratosphere or even those that track through the condensed atmosphere of the poles must account for enhanced radiation exposure during times of increased solar activity. The main concern lies in accumulated exposure on repeated flights during such conditions, not in an incapacitating dose leading to acute radiation sickness. Other common impacts to aviation include interference to both navigation and communications signals caused by a disturbed ionosphere, that portion of the upper atmosphere that reacts to incoming charged solar particles. These examples are just a few of the many impacts from the continuous presence of space weather.

Solar Cycle

As long as the Sun continues its frenetic fusion of hydrogen to helium, it will produce space weather. The frequency and intensity of the

Sun's phenomena are not constant, however, as they correlate to a solar cycle. Determined by counting the number of anomalies, or sunspots, on the sun's surface, a roughly decadal sinusoidal pattern emerges with alternating peaks of heightened activity and relatively quiescent troughs of little to no visible disturbances.[7] The average period between consecutive peaks or troughs averages out to around 11 years.[8] Astronomers determine the actual period only after the fact by observing when the sunspot numbers peak or bottom-out. The current iteration, Solar Cycle 24, steadily rose in the number of sunspots identified after its trough in late 2010. At the time of this writing, the official solar cycle forecast called for a peak of sunspot activity around May 2013.[9] Scientists will not be certain of the max, however, until the peak has well passed and they can trace a smoothed, descending tally of sunspots. Then, after marking a decline for several years, a subsequent increase in sunspot numbers will signify the end of the current cycle.

The Evidentiary Base

A review of the evidentiary base quickly reveals that academia writes most space weather literature and accordingly, tends to focus on the scientific aspects of space weather—basic research into the Sun's natural physical processes that result in the various phenomena. University researchers from across the globe collaborate on papers that endeavor to better represent solar features via mathematical algorithms. In turn, these help to feed the ever more sophisticated experimental models that try to predict such properties as intensity or direction.[10]

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[7] B. B. Poppe and K. P. Jordan, *Sentinels of the Sun: Forecasting Space Weather* (Boulder, CO: Johnson Books, 2006), 25.

[8] Freeman, *Storms in Space*, 56.

[9] "Solar Cycle Progression," Space Weather Prediction Center, http://www.swpc.noaa.gov/SolarCycle/ (accessed 25 January 2013).

[10] Space Studies Board, *Severe Space Weather Events--Understanding Societal and Economic Impacts: A Workshop Report*. (Washington, DC: The National Academies Press, 2008), 4.

Academia often lacks the resources to study the Sun in detail, so has come to rely on the unique capabilities of the National Aeronautics and Space Administration, another significant contributor to the body of scholarship. Primarily a scientific research agency, it has invested considerable resources in the science of space weather, which it calls heliophysics, or "The study of the Sun's influence throughout the solar system and, in particular, its connection to the Earth and the Earth's extended space environment."[11] Whenever possible, the administration seeks to mature products and technologies developed under the heliophysics research program into applications for use by operational agencies more intent on forecasting impacts.[12] An example would include a specific sensor used to simultaneously monitor the Sun in several different wavelengths of light. If, by using that sensor on a research satellite, a discovery reveals a way to earlier spot an impending solar flare, a refined sensor may be included on a National Oceanographic and Atmospheric Administration satellite in order to give operational forecasters more lead-time in issuing a warning to commercial customers.

Recognizing the potentially severe impacts on today's technologically dependent societies, space weather literature has a smaller, but no less significant, applied science focus. Scientists and technology experts have banded together to try and raise awareness about space weather effects on everything from satellites to power grids, to human physiology. In the United States, the National Academy of Sciences has published several lengthy studies and reports over the last

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[11] Brian Dunbar, "The Sun-Earth Connection: Heliophysics Overview," National Aeronautics and Space Administration, http://www.nasa.gov/mission_pages/sunearth/overview/index.html (accessed 22 February 2013).

[12] *Heliophysics: The Solar and Space Physics of a New Era, Recommended Roadmap for Science and Technology 2009–2030*. (Washington, DC: NASA, 2009), 84.

15 years addressing the topic.[13] Similarly, the Royal Academy of Engineering has recently published an evaluation of the United Kingdom's vulnerability to space weather.[14] Of even more practical use, several governmental agencies have invited subject matter experts to observe and participate in table-top exercises between bureaucrats, commercial industry, and partner nations. By bringing together these somewhat disparate stakeholders, both the Department of Homeland Security and US Northern Command have been able to focus attention specifically on security concerns.[15]

A general consensus has emerged from all the literature, whether scientific or operational: space weather deserves significant attention and resources because the catastrophic effects of an Earth-bound severe space weather event could impact hundreds of millions of people and cost trillions of dollars.[16] For the United States and other highly "wired" nations, the largest source of concern in the literature lies with the power grids, mostly because of the potentially destabilizing effect on communities forced to endure weeks, months, or even years without a source of commercial power. The author's review of the literature has helped to broaden the thinking behind this paper as well as it showed how to apply both direct and indirect space weather effects to the national security elements.

Methodology

The method used to derive the conclusions and recommendations presented herein follows from Richard Rumelt's approach to strategy formulation. Rumelt devised what he called a basic strategy kernel of

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[13] Two widely read reports from the National Academy of Sciences include: *Readiness for the Upcoming Solar Maximum.* (Washington, DC: 1998).; and the Space Studies Board, *Severe Space Weather Events*.

[14] *Extreme Space Weather: Impacts on Engineered Systems and Infrastructure*. (London: Royal Academy of Engineering, 2013).

[15] *Managing Critical Disasters in the Transatlantic Domain--The Case of a Geomagnetic Storm: Workshop Summary*. (Boulder, CO: FEMA, 2010). *Secure Grid '11: Electrical Grid Crisis Tabletop Exercise*. (Washington, DC: National Defense University, 2011).

[16] Space Studies Board, *Severe Space Weather Events*. 4.

three elements: diagnosis, guiding policy, and coherent actions.[17] The kernel forms a logical flow from first diagnosing the issue at hand to then issuing a guiding policy that deals with that diagnosed problem. It culminates with a set of coherent actions that implement the policy in a coordinated fashion.[18] In this thesis, chapters 1 through 4 carry out a thorough diagnosis of the challenge, while chapter 5 sets the guiding policy and accompanying coherent actions.

In line with the first phase of the kernel, diagnosing the challenge of space weather involved extensive research into primary sources, to include peer-reviewed scientific journals and government reports on the subject matter. Historical case studies contextualized space weather impacts by giving concrete examples and allowing for the contrasting of events. Chapter 3 used some components of the military's operational design process, namely, center of gravity identification and critical factor analysis, to provide support for fundamental elements of the argument.

The study of the different approaches to space weather by various government agencies has helped distinguish the emphasis placed on multiple aspects of the solar phenomena as some agencies focus more on monitoring and predicting space weather while others concentrate their efforts on addressing the impacts. Particular attention was paid to approaches devised to protect critical space and terrestrial-based assets, as well as resources allocated towards those plans. The above context formed the basis of the policy prescription that will be presented in chapter 5.

Limitations of This Study

As stated previously, plentiful literature exists on the science of space weather with relatively limited coverage of space weather impacts on today's technologically dependent society. Accordingly, this

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[17] Richard Rumelt, *Good Strategy, Bad Strategy: The Difference and Why It Matters* (New York: Crown Business, 2011), 77.
[18] Rumelt, *Good Strategy, Bad Strategy*, 77.

monograph does not attempt to explain the physical mechanics of space weather. Rather, it approaches the subject in an applied fashion by addressing the impacts and advocating for more awareness about space weather in regard to the US national security apparatus.

That said, America has irrevocably tied its security to close allies such as Canada and the United Kingdom. So while the issues raised herein apply to many other industrialized states, the focus will remain on the United States with an inevitable diversion to the potential contributions of partner nations. For instance, the southern hemisphere nation of Australia presents an excellent opportunity for collaboration due to its position on the opposite side of the globe. Through a partnership between the US Air Force and the Australian government, the country's favorable location allows for the exceptional sighting of a jointly administered solar observatory that ensures uninterrupted surveillance of the Sun in all seasons.[19]

Another limitation includes the restriction of this paper to solar-produced phenomena, much like the aforementioned heliophysics definition[20]. This eliminates consideration of other potentially significant space weather phenomena such as the cosmic ray event that saturated the Earth's atmosphere with radiation circa AD 775.[21] While a consensus has not been reached on the source of the intense radiation, researchers have identified a few plausible explanations that lie outside the Solar System, yet still within Earth's galactic home, the Milky Way. The most prominent accounts include a stellar gamma-ray burst or a star going supernova, two extremely powerful explosions caused by

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[19] "Learmonth Solar Observatory," (Sydney: Ionospheric Prediction Service, 2012). Learmonth Solar Observatory sits near the city of Exmouth on the West Australian coast.

[20] Defined by NASA as, "The study of the Sun's influence throughout the solar system and, in particular, its connection to the Earth and the Earth's extended space environment." See Evidentiary Base sub-section and footnote 11, above.

[21] V. V. Hambaryan and R. Neuhauser, "A Galactic short gamma-ray burst as cause for the 14C peak in AD 774/5," *Monthly Notices of the Royal Astronomical Society* 430, no. 1 (2013): 32-36.

colliding stars or a dead, collapsing star, respectively. Regardless of the radiation's origin, it is most important to note that a similar event today would likely cause "great damage to modern technology."[22]

This paper also excludes consideration of astronomical features unrelated to the Sun, such as asteroids or meteoroids. The space weather definitions put forth earlier purposely omitted such objects. Equally, the literature review revealed no linkage has been established between interplanetary bodies and space weather by the heliophysics community. Still, two examples below from early 2013 demonstrate that interplanetary objects have definite national security implications. In February 2013 the Earth experienced a cosmological near miss when a large asteroid passed within the planet's geostationary satellite orbit ring.[23] Just hours before, a meteor exploded over Russia producing a multi-kiloton blast with blinding flash and shockwave—no telescopes observed it coming.[24] Thus, while asteroid tracking justifiably remains a vital component of space situational awareness, it lies outside the scope of a paper strictly focused on space weather.[25]

Summary

The average 11-year solar cycle presents both opportunities and challenges. For the optimist, it gives a few years of reduced risk that allows for preparation before the next peak in solar activity. For the pessimist, that same respite means several years of little to no significant impacts and, correspondingly, less attention being paid to the issue. Given the many competing priorities for national security policy makers,

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[22] Adrian L. Melott and Brian C. Thomas, "Causes of an AD 774-775 14C Increase," *Nature* 491, no. 7426 (2012): E1-E2.
[23] D. Yeomans and Chodas P., "Asteroid 2012 DA14 To Pass Very Close to the Earth on February 15, 2013," NASA/JPL Near-Earth Object Program Office, http://neo.jpl.nasa.gov/news/news177.html (accessed 31 May 2013).
[24] D. Yeomans and Chodas P., "Additional Details on the Large Fireball Event over Russia on Feb. 15, 2013," NASA/JPL Near-Earth Object Program Office, http://neo.jpl.nasa.gov/news/fireball_130301.html (accessed 31 May 2013).
[25] Near-Earth asteroids and meteor impacts are valid threats and deserve an appropriate level of attention un-afforded by this paper.

the cyclical lull in activity might lead many to overlook or unintentionally neglect the potentially devastating impacts of space weather. Seizing on the increased awareness due to the current projected solar maximum, this paper seeks to widen the decision-maker's aperture at a moment when initiated change may have enough time to lead-turn the next solar maximum around 2024. After surveying the known history of space weather and its impacts, this paper will then reflect on why the increasing threat from space weather has not garnered more attention among policy makers and defense leadership. It will subsequently examine several case studies from the US government using representative agencies from the National Space Weather Program council. Finally, it will recommend a general policy to guide specific actions that both policy makers and military leadership can accept. One recommendation certain to be included: the Department of Defense, in order to mitigate critical vulnerabilities to national security, should seek unified action at the interagency, private sector, and academic levels as well as among partner nations to ensure space weather effects are addressed comprehensively.

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Chapter 2

Historical Impacts

One swallow does not make a summer.
Richard C. Carrington, Esq., 1859

For as long as stars have shone, space weather has blown through the universe. The aforementioned saturation of the Earth by radiation in the eighth century attests to the occurrence of space weather over the millennia of human experience. While astronomers have pondered the origin of that particular event, a recent scientific paper submits that a short gamma-ray burst within the Milky Way galaxy most likely released the energy.[1] Such bursts emanate from the near instantaneous fusion of colliding objects such as two massive neutron stars.[2] With the universe continuing to expand and billions of stars orbiting in dense galaxy clusters, such explosions, while rarely observed, are bound to find the Earth in their path again.

More recently, within just the last few centuries, man began to make regular observations of the Sun and unwittingly identified features associated with the still unknown space weather. Galileo Galilei, an astronomer made famous by observations with his self-built telescopes, turned his lenses upon the Sun in 1610 and joined other scientists trying to determine the nature of aptly named "sunspots."[3] Successive generations of astronomers devoted greater study to the Sun and kept detailed logs of sunspot activity. From this, a cyclical pattern began to

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[1] V. V. Hambaryan and R. Neuhauser, "A Galactic short gamma-ray burst as cause for the 14C peak in AD 774/5," Monthly Notices of the Royal Astronomical Society 430, no. 1 (2013): 32-36.
[2] Hambaryan and Neuhauser, "A Galactic short gamma-ray burst as cause for the 14C peak in AD 774/5," 32-36.
[3] M. J. Carlowicz and R. E. Lopez, *Storms from the Sun: The Emerging Science of Space Weather* (Washington, DC: The Joseph Henry Press, 2002), 60.

emerge that has been faithfully documented since the mid-eighteenth century.[4] Even with all these discoveries, no one had yet drawn a connection between phenomena observed on the Sun with a terrestrial impact. It would take a major space weather event to finally comprehend the relationship.

The Carrington Event

The rather fantastic course of events outlined in the introductory chapter actually occurred over several days in early September 1859 as the world stood poised to make a second great push in the industrial era. Widely known by the surname of the British astronomer, Richard Carrington, who first published his observations of the catalyst, the Carrington Event marked the first recorded sighting by Carrington and his colleague, Richard Hodgson, of what later became known as a solar flare. While working just before noon in separate observatories about 25 miles apart, they simultaneously witnessed a "brilliant" flash of white light on their projected images of the Sun.[5] Unlike anything either had previously observed, each quickly noted the time and other relevant details. Later, their notes would serve to corroborate each other as well as hint at a possible connection with the unprecedented measurements from a magnetometer stationed between them in London.[6]

Even with the astronomical phenomenon documented by Carrington and Hodgson, the event might have ended up as just footnote in geophysical studies were it not for its peculiar impact on the most advanced communication system of the day, the telegraph. Albeit a still relatively immature technology in 1859, an ever-expanding civilization came to depend on the telegraph as a vital means to connect the

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[4] "Sunspot index graphics," Solar Influences Data Analysis Center, http://sidc.oma.be/html/wolfaml.html (accessed February 28, 2013).

[5] R. Hodgson, "On a curious Appearance seen in the Sun," *Monthly Notices of the Royal Astronomical Society* 20, no. 1 (1859): 15-16.

[6] R. C. Carrington, "Description of a Singular Appearance seen in the Sun on September 1, 1859," *Monthly Notices of the Royal Astronomical Society* 20, no. 1 (1859): 13-15.

frontiers.[7] Now the network sat nearly idle as a strong induced current from a presumably natural source overcharged the transmission wires. As the power dissipated over time and these critical communications hubs managed to transmit effectively again, a partial picture emerged slowly as telegraph operators began exchanging their experiences. Operators of the sole means for long-line message traffic, the specialists not only shared personal anecdotes with each other, but also took responsibility for collecting the many widespread sightings of Northern and Southern Lights reported in the far equatorial latitudes.[8] Although connected to most important lines of communications available, the technicians could not begin to fathom a linkage with the Sun or even the worldwide extent of the effects. Present-day scientists have distinguished the Carrington Event as "one of the largest magnetic storms in recorded history" and "the largest space weather event in over 400 years."[9]

Great Geomagnetic Storm of May 1921

While no recorded event has reached the level of intensity estimated in the Carrington Event, several solar-induced tempests have gained notoriety over the years. As an example, the "Great Geomagnetic Storm of May 1921" has risen in prominence because of studies recently undertaken using modern techniques not available to past researchers. New estimates of the storm's intensity have added to the historical record while also causing concern among scientists who understand the impacts such an event would have on the twenty-first century.

In a similar way to the 1850 episode, the 1921 event interrupted communications, caused electrically induced flare-ups, and displayed an

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[7] B. Barr, "Map of Telegraph Stations in the United States, the Canadas, and Nova Scotia.," (Pittsburgh: Wagner and Beuchnerlith, 1835).
[8] Carlowicz and Lopez, *Storms from the Sun*, 53-60.
[9] P. Riley, "On the probability of occurrence of extreme space weather events," *Space Weather* 10, no. 2 (2012): 1-12.

amazing aurora.[10] As telegraph and even wireless networks had spread to many more locations around the globe, widespread disruptions were reported in addition to more severe fire damage. Incredibly, scientists reported sighting aurora within 13 degrees of the magnetic equator, although it probably only extended overhead to about 40 degrees geomagnetic latitude.[11]

What has really piqued interest in the 1921 storm is recent physical valuations of its strength. When compared to actual measurements taken by instruments over the last 50 years, the 1921 storm would rank at the top with approximately 50 percent more energy transferred than the number two storm described in the next section.[12] A commonly accepted measure of geomagnetic storm intensity would have assigned the 1921 storm an approximate rating of -900.[13] Anything less than -500, *i.e.* more negative, is considered a rare geomagnetic

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[10] S. M. Silverman and E. W. Cliver, "Low-latitude auroras: the magnetic storm of 14–15 May 1921," *Journal of Atmospheric and Solar-Terrestrial Physics* 63, no. 5 (2001): 523-35.

[11] Silverman and Cliver, "Low-latitude auroras: the magnetic storm of 14–15 May 1921," 523-35. A. Pulkkinen et al., "Generation of 100-year geomagnetically induced current scenarios," *Space Weather* 10, no. 4 (2012): 1-19. For reference on magnetic equator, National Geophysical Data Center modeling in January 2010 projected the geomagnetic zero degree line lying within 10 to 15 degrees of the geographic equator found at zero degrees of latitude as depicted in map from S. Maus et al., "Main Field Inclination (I)," in *The US/UK World Magnetic Model for 2010-2015, NOAA Technical Report NESDIS/NGDC* (NOAA, 2010).

[12] J. Kappenman, "Great geomagnetic storms and extreme impulsive geomagnetic field disturbance events – An analysis of observational evidence including the great storm of May 1921," *Advances in Space Research* 38, no. 2 (2006): 188-99. *Halloween Space Weather Storms of 2003*. NOAA Technical Memorandum OAR SEC-88. (Boulder, CO: National Oceanic and Atmospheric Administration, 2004), 28.

[13] Kappenman, "Great geomagnetic storms and extreme impulsive geomagnetic field disturbance events – An analysis of observational evidence including the great storm of May 1921," 188-99. The measure referenced here is called the "Storm-time Disturbance Index" (Dst) and the NOAA Halloween Storms report (2004) describes it as a global index "devised as a means of characterizing the level of disturbance in the equatorial regions." The NOAA report (2004) goes onto to say that, "The degree and extent of (the Earth's geomagnetic field north-south horizontal component) depression has proven to be a useful characterization of the energy transfer from the solar wind into the Earth's magnetosphere and is an estimate of the energy density of energetic particles in Earth's ring current." It is measured in nanotesla (nT).

superstorm with only one event actually captured by instruments.[14] Of most concern, however, is the projected rate-of-change of the geomagnetic field during the 1921 event. It is this rapid fluctuation of the Earth's field caused by geomagnetic storming that induces the current in long-line power cables.[15] A paper published by Metatech Corporation estimates the geomagnetic field change per minute in the 1921 storm to be approximately -5000 nanotesla per minute.[16] Without concern for the units of measurement, it suffices to point out that the geomagnetically induced current, commonly referred to as a "GIC," outlined in the next section resulted from an impulse, or rate-of-change, of less than one-tenth the 1921 event just described.[17] Recall this potential strength while trying to conceptualize the significant havoc a storm of such magnitude might wreak on the stressed power grids of today.

The 1989 cascading power failure

When initially viewed from the Earth, it appeared as just a small gouge on an otherwise perfect outline of the Sun's normally circular periphery. As the Sun's rotation brought the cavity into view, however, it became quickly apparent that this blemish was unlike anything ever witnessed in the modern era of solar physics. Directly observed by an extraordinary array of purpose built instruments for the first time, physicists and solar forecasters soon had an unprecedented awareness

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[14] G. S. Lakhina et al., "Research on Historical Records of Geomagnetic Storms," *Proceedings of the International Astronomical Union* 2004, no. IAUS226 (2004): 3-15. *Halloween Space Weather Storms of 2003*. 28. For comparison, Lakhina et al., estimate the Carrington Event reached a Dst of approximately -1760 nanotesla (nT) (p 10). They also document the March 1989 event, the one superstorm actually recorded with modern instruments, topping out at -589 nt (Table 1 on p 14).

[15] Kappenman, "Great geomagnetic storms and extreme impulsive geomagnetic field disturbance events – An analysis of observational evidence including the great storm of May 1921," 188-99.

[16] Kappenman, "Great geomagnetic storms and extreme impulsive geomagnetic field disturbance events – An analysis of observational evidence including the great storm of May 1921," 188-99.

[17] Kappenman, "Great geomagnetic storms and extreme impulsive geomagnetic field disturbance events – An analysis of observational evidence including the great storm of May 1921," 188-99.

of “the most complex sunspot region” they had ever faced.[18] Yet, as a relatively nascent scientific field, they still lacked sufficient fidelity on the potential downstream effects to the Earth and its near-space environment.

Just as the sunspot region started to move into direct alignment with the Earth, space-based sensors spotted a solar flare eruption followed by a rapidly expanding ring of light all around the sun. This “halo” effect, the result of the relatively dense edge of a particle cloud as captured by optical cameras, indicated a coronal mass ejection heading for the Earth. Forecasters issued an advisory for significant geomagnetic storming in about 48 to 36 hours. True to their prediction, the event that began on 12 March developed into the third strongest geomagnetic storm measured to date.[19]

Impacts were widespread. The ejected mass had compressed the Earth’s magnetic field, the magnetosphere, to around half its normal radius, forcing it to contract well inside the ring of vital geostationary satellites.[20] The orbit of these satellites hold them in a relatively stable position at around 36,000 kilometers above the equator where they are generally well protected from the Sun.[21] In this case, however, their delicate sensors and electronics took the full brunt of the surging solar wind and all the hazards carried along with it.

Closer to the Earth, the coronal mass ejection and resultant geomagnetic storm energized particles trapped in the outer atmosphere,

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[18] Carlowicz and Lopez, *Storms from the Sun*, 94.
[19] *Halloween Space Weather Storms of 2003*. 26. As previously noted in the conclusion of the discussion on the 1921 Great Geomagnetic Storm, the 1921 storm was approximately ten times as intense as this 1989 storm that caused the cascading power failure. Lakhina et al., document the March 1989 event, topping out at -589 nanotesla (nt) (Table 1 on p 14) where John Kappenman of Metatech estimated the 1921 storm at a Dst of approximately -5000 nt (2006). See notes 13 and 14 for an explanation of Dst and units of measure.
[20] Carlowicz and Lopez, *Storms from the Sun*, 96.
[21] Space-track.org, "Geosynchronous Report," Scitor, https://www.space-track.org/basicspacedata/query/class/satcat/format/html/orderby/NORAD_CAT_ID/PERIOD/1430--1450/CURRENT/Y/DECAY/null-val (accessed 5 May 2013).

pushing them to a frenetic pace. All the excess heat energy expanded the ionosphere such that it essentially pushed back against the intrusive cloud from the Sun. This compacting of the normally sparse gas molecules in low earth orbit increased the atmospheric density and concomitant drag so much that the US Air Force lost thousands of orbital tracks.[22] Objects in normally predictable paths around the Earth had slowed so much that their orbits began to decay. While orbital decay can be a good thing when so-called "space-junk" descends into the atmosphere and burns up, a satellite that falls prey to its effects can have a significantly reduced service life and/or lose contact with ground stations. Such was the case of a US military satellite in low-earth orbit that started an unrecoverable gyration during the event—once the antennas orientated away from the Earth, helpless controllers could only hope the tumbling satellite did not collide with another before it eventually fell out of orbit.[23]

Perhaps the most significant impact due to both its breadth and implications came on 13 March when geomagnetically induced currents along five major power lines in Quebec caused built-in safety mechanisms to trip nearly simultaneously. Losing almost 50 percent of its available power on a freezing Canadian night led the largest hydroelectric system in the world to collapse in just 90 seconds.[24] More than 6 million residential and business customers lost power for the rest of the night and morning.[25] Before it was done, the loss of expensive network infrastructure as well as productivity netted an estimated economic loss of around $2 billion.[26]

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[22] Carlowicz and Lopez, *Storms from the Sun*, 97.
[23] Carlowicz and Lopez, *Storms from the Sun*, 97.
[24] Space Studies Board, *Severe Space Weather Events--Understanding Societal and Economic Impacts: A Workshop Report.* (Washington, DC: The National Academies Press, 2008), 18, 109-11.
[25] Carlowicz and Lopez, *Storms from the Sun*, 100.
[26] C. J. Schrijver, "Solar Maximum 2013--How Space Weather Will Affect You!" (paper presented at the 2012 Space Weather Enterprise Forum, Washington, DC, 5 June 2012), 11.

The impacts did not stop there, however. Of greatest concern, the Quebec hydroelectric system feeds directly into the US network and the sudden loss in power placed acute stress on the Northeast power grid. Given the early hour and milder temperatures in the United States, excess power capacity barely maintained the network even while utilities struggled to bring reserves online.[27] Retrospectively, American operators admitted their system nearly succumbed to a cascading failure that most likely would have extended to the US mid-Atlantic and even as far as the Midwest.[28]

The American network did not emerge totally unscathed from the event. Caused by the same induced current phenomena, but unrelated to the Canadian failure, components on a $10 million transformer at a New Jersey *nuclear* power plant melted as a result of the overcharge.[29] Besides the fact that this had the potential to cause a fire at a nuclear facility, this critical power feed to the northeast megalopolis would have experienced an extended period offline had a spare not been readily available—typically such a large piece of specialized equipment requires a year of manufacturing.[30] Both of these events served as a wake-up call to an industry that had effectively ignored warnings and dismissed prior incidents.

The 2003 Halloween storms

Space weather observers and forecasters did not anticipate an exciting year in 2003. Solar cycle 23 had already experienced its peak in the spring of 2000 and after a smaller double peak, sunspot numbers continued on a downward trend.[31] Yet, 42 months after the max, in a relative lull, "three large and complex sunspot regions" emerged "with

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27 S. Odenwald, "The Day the Sun Brought Darkness," National Aeronautics and Space Administration, http://www.nasa.gov/topics/earth/features/sun_darkness.html (accessed 7 April 2013).
28 Space Studies Board, *Severe Space Weather Events*. 105.
29 Carlowicz and Lopez, *Storms from the Sun*, 98-99.
30 Carlowicz and Lopez, *Storms from the Sun*, 99.
31 *Halloween Space Weather Storms of 2003*. 2.

little warning" and caused almost continuous significant impacts for three straight weeks.[32]

Over that period, a barrage of solar flares shot from the three regions, ten of which reached the highest threshold for energetic events, X-class.[33] A truly exceptional X-class flare on 4 November overwhelmed space-based X-ray sensors, allowing for only an estimated strength of X28. While scientists had already pegged the flare as the strongest ever rated, over a year later they revised their estimate upward to a magnitude X40.[34] For comparison, the previous record flare on the linear scale measured an X20 (also estimated), making the 4 November eruption approximately twice as powerful as any previously recorded solar flare.[35]

Almost immediately following each record flare, a rapidly expanding coronal mass ejection wildly flung huge sums of solar matter out into space. Moving at twice their normal pace, those heading generally in the Earth's direction slammed into its magnetic shield, resulting in two of the strongest geomagnetic storms on record.[36] One flare also unleashed a speedy stream of particles that peaked space-based radiation counters at their fourth highest level since standardized measurements started in 1976.[37] All told, the 2003 Halloween Storm persisted for 20 straight days with one particularly intense stretch of 96 hours where instrument readings indicated nearly non-stop severe or greater impacts.[38]

While these figures may sound impressive, the impacts matter most because they answer the "So what?" question. Due to this

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[32] *Halloween Space Weather Storms of 2003*. 2, 6.
[33] *Halloween Space Weather Storms of 2003*. 45.
[34] D. Brodrick, Tingay, S., and Wieringa, M., "X-ray magnitude of the 4 November 2003 solar flare inferred from the ionospheric attenuation of the galactic radio background," *Journal of Geophysical Research: Space Physics* 110, no. A9 (2005).
[35] *Halloween Space Weather Storms of 2003*. 12.
[36] *Halloween Space Weather Storms of 2003*. 26-27.
[37] *Halloween Space Weather Storms of 2003*. 24.
[38] *Halloween Space Weather Storms of 2003*. 44.

extraordinary series of events in 2003, the National Weather Service concluded that nearly all "industries vulnerable to space weather experienced some degree of impact to their operations."[39] Astronauts in the International Space Station curtailed their normal duties to take cover in shielded compartments. Numerous government and commercial satellites went into safe mode or temporarily lost contact with ground stations. Operators never regained control of at least one satellite only months into its three-year science mission. Airlines diverted long-haul, high-latitude flights towards the equator in order to maintain radio contact and minimize radiation exposure. As a result of lessons learned from the 1989 cascading power failure, electrical companies took prompt action and averted the most severe impacts to their grids. "Extreme" rated geomagnetic storming still caused at least one short-term blackout in the high northern latitudes.[40] Likewise in the high southern latitudes, the storm knocked out 15 South African power transformers, five of them went down permanently.[41]

As for impacts to national security, it is worth recalling that during this period of incredible activity the United States and its allies had troops engaged in combat on multiple fronts. Often operating in isolated environments such as the mountains of Afghanistan or the Philippine archipelago, these troops depended on America's space-based infrastructure as a vital means for navigation, surveillance, and communications. To mitigate lasting impacts to these and other operational missions around the globe, the US Air Force Space Command made the decision to shut down components on several satellites in order to prevent anomalies already plaguing some of its

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[39] *Intense Space Weather Storms October 19-November 07, 2003*. National Weather Service Assessment. (Silver Spring, Maryland: NOAA, 2004), 1.

[40] *Halloween Space Weather Storms of 2003*. 32-37.

[41] MITRE, *Impacts of Severe Space Weather on the Electric Grid*. JASON Summer Study 11-320. (McLean, Virginia: DHS, 2011).

spacecraft.[42] While normally a prudent preservation technique, placing sensors or transmitters in safe mode has essentially the same effect on end-users as a satellite knocked offline by a high-speed proton—no functionality. This fact must be weighed against the need to safeguard these critical assets from lasting damage.

2013 Solar Maximum?

Nearly a decade after the Halloween storms of 2003, with forces still engaged around the globe, the United States faces the next period of predicted maximum solar activity (see Figure 1 below for latest projections). Will the Sun unleash a major solar flare or coronal mass ejection in 2013 on par with the aforementioned events? Will the Earth's orbital path around the Sun carry it into an extreme rush of solar wind?

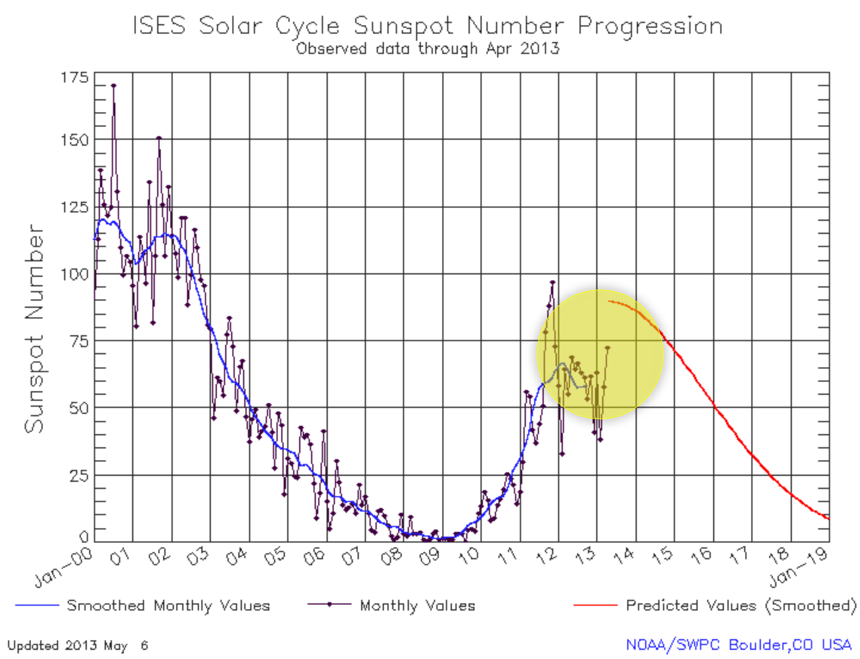

Figure 1: International Space Environment Service (ISES) solar cycle sunspot number progression as of 6 May 2013; yellow highlighting shows gap between actual (smoothed, blue line) and predicted (bell-shaped, red line) monthly sunspot number

Source: http://www.swpc.noaa.gov/SolarCycle/

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[42] *Halloween Space Weather Storms of 2003*. 34.

At least one solar scientist has calculated odds that should give pause to those concerned about national security. In 2012, the journal *Space Weather* published the mid-2011 conclusions of Dr. Pete Riley who stated, “the probability of another Carrington event…occurring within the next decade is ~12%.”[43] He goes on to add that given the Carrington Event’s unprecedented strength over a 400-year span and its relatively recent occurrence approximately 150 years ago, it should serve as “a constant reminder that a similar event could reoccur any day.”[44]

Dr. Riley’s prediction notwithstanding, the unexpectedly low sunspot number in early 2013 compelled the lead physicist on the US Solar Cycle Prediction Panel, Dr. W. D. Pesnell, to reassess the original forecast for a May 2013 maximum.[45] Instead of a single activity peak for the 11-year cycle, Dr. Pesnell now predicts a not uncommon second surge of activity to peak in late 2013 or early 2014.[46] As already shown, however, the most intense solar storms do not necessarily correlate with total sunspot number and so should the forecasted double-peak not materialize, stakeholders should maintain vigilance while continuing risk mitigation.

As of this writing, neither scientists nor operators have reported any major space weather effects on or near the Earth in 2013. Engineers at the Jet Propulsion Laboratory, however, continue to investigate a probable space weather impact on the latest Mars rover, *Curiosity*. The main computer on the $2.5 billion rover experienced a problem with its flash memory in late February, less than seven months into its geological

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[43] P. Riley, "On the probability of occurrence of extreme space weather events," *Space Weather* 10, no. 2 (2012): 1-12.

[44] Riley, "On the probability of occurrence of extreme space weather events," 1-12. See note 14 for one measure of estimated strength for the Carrington Event by John Kappenman.

[45] Tony Phillips, "Solar Cycle Update: Twin Peaks?," National Aeronautics and Space Administration, http://science.nasa.gov/science-news/science-at-nasa/2013/01mar_twinpeaks/ (accessed 3 April 2013).

[46] Phillips, "Solar Cycle Update: Twin Peaks?," http://science.nasa.gov/science-news/science-at-nasa/2013/01mar_twinpeaks/ (accessed 3 April 2013).

survey.[47] With no alarms or other indications prior to the anomaly, the *Curiosity* project manager speculated a possible "radiation hit" precipitated the glitch.[48]

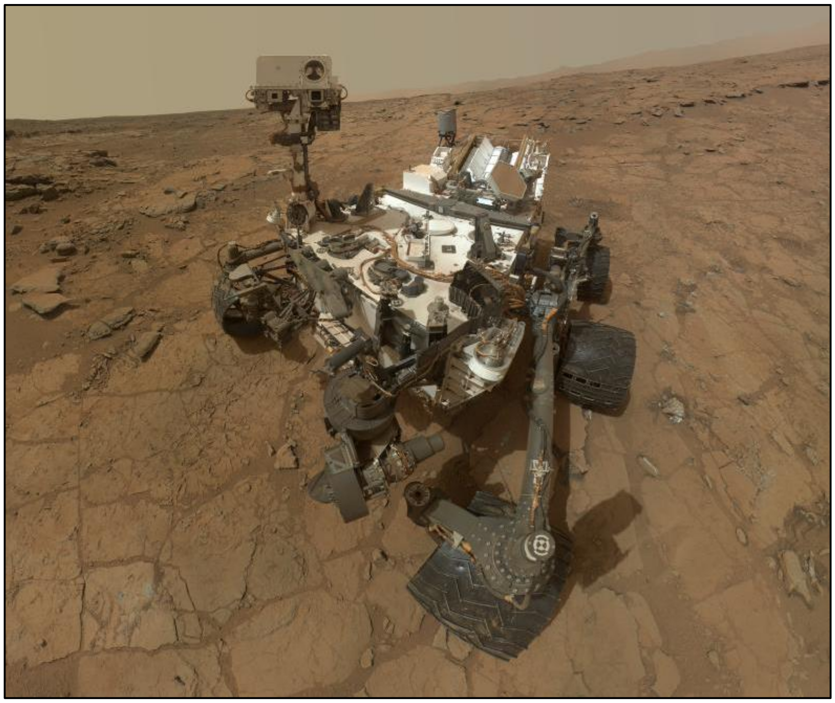

Figure 2: NASA's *Curiosity* rover in a composite self-portrait taken while on the Red Planet

Source: National Aeronautics and Space Administration (http://www.nasa.gov/mission_pages/msl/multimedia/pia16764.html)

If that were not enough, just before the rover was set to resume normal operations on a back-up computer, a strong solar flare and subsequent coronal mass ejection led controllers to suspend the

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47 Irene Klotz, "Computer glitch suspends NASA Mars rover operations." *Reuters.com*, 2013. http://www.reuters.com/article/2013/03/05/space-mars-idUSL1N0BWKM020130305 (accessed 5 March 2013).

48 Klotz, "Computer glitch suspends NASA Mars rover operations." http://www.reuters.com/article/2013/03/05/space-mars-idUSL1N0BWKM020130305 (accessed 5 March 2013).

operations restart in order to keep the robot safe in sleep mode.[49] Unlike the Earth, Mars does not have a natural magnetic field to shunt the harmful particles around the planet.[50] So while the red planet orbits more than one and half times the distance between the Sun and Earth, the sheer reach of space weather makes it a primary concern for engineers of spacecraft travelling outside the relatively safe confines of the Earth's magnetosphere. *Curiosity* eventually overcame the fault to carry on its projected multiyear science mission, but engineers have yet to definitively assign a root cause of the malfunction. The example above demonstrates the precarious nature of space travel when even spacecraft specifically designed and built to withstand the harsh environment can succumb to solar effects.

Summary

Although it occurred over 150 years ago, the Carrington Event offers many lessons for the "operators" of today. In an era where electronic technology extends to almost every aspect of life, where information is often the most important commodity and national security rests on a foundation of interconnected systems, a major space weather event has the possibility to severely disrupt life and cause untold damage to society. Although relatively harmless in a less technologically dependent world, it's worth heeding the quirky caveat that Carrington submitted in his report to the Royal Astronomical Society. Speaking to the tenuous connection between the Sun's incredible display on September 1st and the "great magnetic storm" that followed shortly thereafter, Carrington warned, "One swallow does not make a summer."

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[49] Alicia Chang, "Curiousity sleeps as solar blast races toward Mars." *AP.org*, 6 March 2013. http://hosted.ap.org/dynamic/stories/U/US_SCI_MARS_WEATHER?SITE=AP&SECTION=HOME&TEMPLATE=DEFAULT (accessed 8 March 2013).

[50] Chang, "Curiousity sleeps as solar blast races toward Mars." http://hosted.ap.org/dynamic/stories/U/US_SCI_MARS_WEATHER?SITE=AP&SECTION=HOME&TEMPLATE=DEFAULT (accessed 8 March 2013).

To that point, the Carrington Event and other historical examples provided do not show a definitive trend. Instead, they offer clues to how a future recurrence might impact an ever more technologically reliant society. As the Carrington Event has not been surpassed since in terms of intensity felt on the Earth, should Dr. Riley's computations prove correct and a similar event occur in the not too distant future, it would almost certainly catch the world by surprise and result in an economic and social catastrophe as people struggle to adapt to life anew. While an admittedly dire picture, policy makers and operators alike should not dismiss this threat and instead seek to understand the phenomena and their impacts to national security.

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Chapter 3

Critical Factors

"I know you what you are, and was sure that I should not move you, for your heart is hard as iron; look to it that I bring not heaven's anger upon you on the day when Paris and Phoebus Apollo, valiant though you be, shall slay you at the Scaean gates."

A vanquished Hector to his conqueror, Achilles, in Homer's *Iliad*

One could argue that in a grand strategic sense, the Department of Defense forms the center of gravity for the US national security enterprise. If allowed to continue this abstraction for the sake of argument, an analysis of the department reveals certain critical factors that not only demonstrates its centrality to national defense, but also its principal weaknesses. This chapter focuses on three critical requirements the Department of Defense relies on that are also most susceptible to the effects of space weather: 1) space power; 2) electrical energy; and 3) US commercial capacity, which includes both the service and manufacturing sectors. Before addressing the three requirements directly, however, a short departure to outline the process of critical factor analysis will justify selection of the three requirements above, and ultimately the critical vulnerabilities. The process starts with the foundational notion of the center of gravity.

Center of Gravity

Carl von Clausewitz, the oft-cited nineteenth century Prussian general, famously applied the physical concept of center of gravity,

translated from the German *Schwerpunkt*, to warfare.[1] In book 8 of his seminal work, *Vom Kriege,* Clausewitz dealt with the "problem of war as a whole" and "its most important aspect: pure strategy."[2] Perhaps in an allusion to his forthcoming wider application of *Schwerpunkt*, he described pure strategy as the "central point on which all other threads converge."[3] Within this greater context he further developed *Schwerpunkt* beyond just an operational or tactical concept, labeling the center of gravity as the "hub of all power and movement, on which *everything* depends" (emphasis added).[4]

So in application to the US national security enterprise, would Clausewitz have labeled the Department of Defense as its center of gravity? If he had correctly concluded the department embodied the military in its entirety, he almost certainly would have. For in the contest of war, Clausewitz believed the "grand objective of all military action is to overthrow of the enemy" by directing all "energies" against "destroying his armed forces."[5] Thus, in the Clausewitzian sense of a pure duel, the Department of Defense represents the center of gravity, but does that transfer to the impact of space weather upon US national security, the argument of this thesis? The answer is, "yes," based upon

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[1] *Schwerpunkt* is a conjunction of the two German words for "heavy" and "point." The "heavy-point" is an apt synonym for center of gravity. Dr. Hal Winton, professor of military history and theory, School of Advanced Air & Space Studies (SAASS), cautions his SAASS 600 students that other translations exist. Dr. Winton writes in his syllabus, "be alive to the fact that [Clausewitz's] discussion of the term 'center(s) of gravity'" is "a valid translation, but not the only valid translation, of the German term(s) *Schwerpunkt(en)*."

[2] Carl von Clausewitz, *On War*, trans. Michael Howard and Peter Paret, Indexed ed. (Princeton, NJ: Princeton University Press, 1976), 577.

[3] Clausewitz, *On War*, 577.

[4] J. Strange and R. Iron, *Understanding Centers Of Gravity and Critical Vulnerabilities* (Stockholm: Swedish National Defence College, 2005). From Strange and Iron comes the idea that Clausewitz's center of gravity definition differs in in his various chapters of *On War*. Thus, they warn, the context of the particular book (*On War* is divided into eight books) and chapter must be carefully considered before comprehension and discussion. Clausewitz, *On War*, 577-78. This definition of center of gravity comes from Chapter 4, Book Eight, "War Plans." As implied by the title, Clausewitz discusses herein the "planning of a war and a campaign" and clearly applies this thinking to the higher, or strategic, level of conflict, for lack of a more appropriate modifier.

[5] Clausewitz, *On War*, 577. 596.

another Clausewitzian notion of the subject, that of an entity's "dominant characteristics" forming the basis for the center of gravity.

When reviewing the US national security enterprise, a few key variables standout as defining characteristics—its people, its budget and, its sheer power, especially when considering its nuclear arsenal.[6] By almost any measure, but especially these three, the Department of Defense dominates US national security. In 2012, it had approximately 2.2 million full-time employees, spending that represented 18 percent of total federal budget, and myriad weapons that were backed up by a powerful nuclear deterrent.[7] So while space weather does not represent

[6] Clausewitz, *On War*, 595.

[7] According to the Office of the Secretary of Defense Statistical Information and Analysis Division (http://siadapp.dmdc.osd.mil/personnel/MMIDHOME.HTM), the Department of Defense had approximately 2.2 million full-time employees as of 31 December 2012. This included 1,385,055 active duty soldiers, sailors, marines, and airmen, 742,582 full-time civilians, and another 76,555 full-time members of the active guard reserve (AGR). An additional 56,218 members of the six reserve components were in federal status or activated as of 18 December 2012 but not counted, as cited in "Reserve Components," Defense Manpower Data Center, http://www.defense.gov/news/MobilizationWeeklyReport121812.pdf (accessed May 24, 2013). In addition, these numbers do not count over one million members of the non-activated ready reserve and auxiliary components. Lastly, the Department of Defense utilizes many thousands of contractors who work full-time for the department but are actually employed through their contractor. While these numbers are projected to decrease in the coming years due to budgetary pressures and reduced requirements, the large total provides just one measure of national security dominance for the Department of Defense. Indeed, the department was the single largest employer in the world in 2010 with about 3.2 million employees, as cited in, "Defending Jobs," The Economist Online, http://www.economist.com/blogs/dailychart/2011/09/employment (accessed May 23, 2013). Furthermore, the US Census Bureau estimates the 2012 US population to be 313,914,040, as cited in, "USA QuickFacts," US Census Bureau, http://quickfacts.census.gov/qfd/states/00000.html (accessed 27 May 2013). Given these numbers, the Department of Defense employs about one percent of the total US population. Looking at another measure of dominance—budgetary authority—published reports from the White House Office of Management and Budget (http://www.whitehouse.gov/omb/budget/Historicals/) show that in 2012 the Department of Defense garnered over 96% of the national defense "function" with nearly $651 billion in outlays. Furthermore, it received over 18% of all federal budget outlays. These numbers dwarf all other national security related expenditures which make up no more than 3% of total federal budgetary outlays. As one final measure of dominance, the department is responsible for the ultimate underwriter of US national defense against hostile existential threats, its nuclear weapons. While the number of deployed nuclear warheads under control of the department is classified, a 2010 Defense Department fact sheet listed 5,113 warheads in the nuclear stockpile (both active and inactive warheads) as of 30 September 2009 (as cited in DoD Fact Sheet: *Increasing Transparency in the U.S. Nuclear Weapons Stockpile*, 3 May 2010, 2.). This

a physical foe the likes of what Clausewitz envisioned, any threat to the Department of Defense strikes at the very heart of US national security.

Could the same case be made for the US economy as the center of gravity for US national security? After all, as alluded to in the introduction, the national security apparatus depends upon a strong commercial sector to not only provide materiel for national security, but also to drive the economy that in turn pays for the millions of employees and high-technology weapons like nuclear-tipped intercontinental ballistic missiles. Moreover, would not a major blow to the economy that threatens to undermine American social order require prompt National Security Council attention? Again turning to Clausewitz, while he did not entirely dismiss the importance of economic factors, he concluded they were an "outside determinant" and rarely touched on them in *Vom Kriege*.[8] In other words, while the economy certainly influences national security, it does not lie within in it. Accepting Clausewitz's explanation that at the grand strategic level, a center of gravity emanates from certain "dominant characteristics," the center of gravity will usually rest between or within opposing forces, as in the case of the Department of Defense lying firmly within the realm of US national security.[9]

Critical Factors

In 1996, Dr. Joe Strange of the Marine Corps War College decided that Fleet Marine Forces Manual 1 lacked sufficient connection between centers of gravity (CG) and a contemporary concept found in the manual,

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total has presumably decreased by a significant number given the fact sheet stated that "several thousand additional nuclear weapons are currently retired and awaiting dismantlement."

[8] Clausewitz, *On War*, 286-87. No less an eminent historian than Sir Michael Howard cited B. H. Liddell Hart and his criticism of Clausewitz in Hart's classic, *Strategy.* In an introductory essay to his translation of *Vom Kriege*, Howard justifies Hart's critique, writing that the Prussian's "ignoring" of economic factors was a "shortcoming" (p 40-41). To his credit, Hart's concept of "limited aim" war factors in economic power, including its use as one "instrument of grand strategy," as cited in B. H. L. Hart, *Strategy: Second Revised Edition* (Plume Books, 1991), 320-23.

[9] Clausewitz, *On War*, 595.

critical vulnerabilities (CV).[10] To reconcile this gap, he proposed two new terms for inclusion in doctrine, critical capabilities (CC) and critical requirements (CR). Altogether, Dr. Strange coined the chain from center of gravity to critical vulnerabilities as the "CG-CC-CR-CV" construct.[11] His definition of each critical factor linked it to the next so that a true analysis, or mental breaking down into constituent parts, of the center of gravity would yield weaknesses ripe for exploitation.[12]

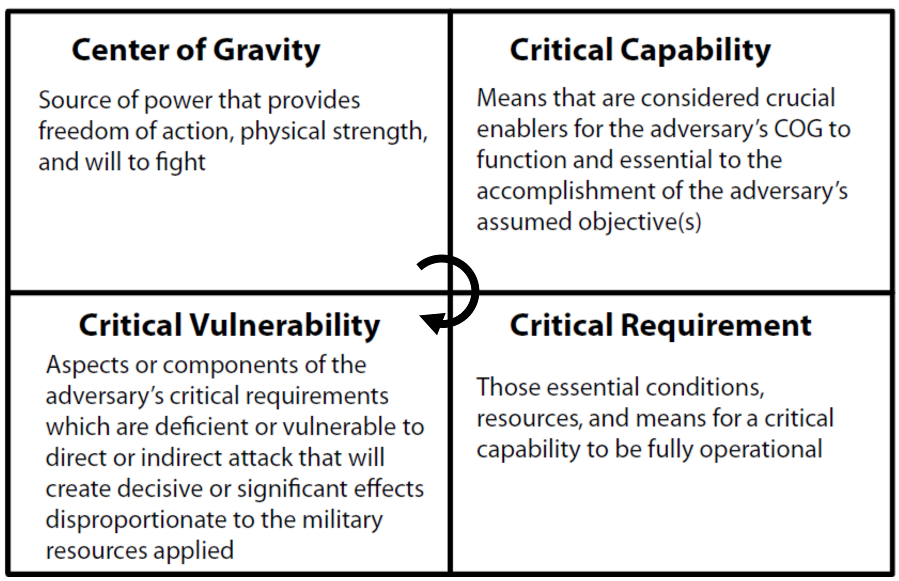

Figure 3: Critical factor analysis model

Source: Operational Design *(Reilly, 2012)*[13]

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[10] J. Strange, *Centers of Gravity & Critical Vulnerabilities: Building on the Clausewitzian Foundation So That We Can All Speak the Same Language*, Second ed., Perspectives on Warfighting (Quantico, VA: Marine Corps University, 1996), 2.

[11] Strange, *Centers of Gravity & Critical Vulnerabilities*, 91.

[12] J. R. Boyd, "Destruction and Creation," (1976). In this paper, John Boyd wrote, "There are two ways in which we can develop and manipulate mental concepts." Basically, a concept like center of gravity can be analyzed or synthesized, that is, "start from a comprehensive whole and break it down to its particulars" or "start with the particulars and build towards a comprehensive whole." From this dialectic he draws the title of his paper, "Destruction and Creation."

[13] J. M. Reilly, *Operational Design: Distilling Clarity from Complexity for Decisive Action* (Maxwell AFB: Air University Press, 2012), 43. Note the clockwise movement from the top-left corner, center of gravity, around to the bottom-left corner, critical vulnerability. The definitions presented in each section of the grid are adapted from those found in official joint doctrine.

Critical Capabilities

Dr. Strange defined a critical capability as some "primary ability (or abilities) which merits a Center of Gravity to be identified as such in the *context* of a given scenario, situation or mission" (emphasis added).[14] He went on to further explain by asking, given the context, "What particular capability are we especially concerned about?"[15] He stressed that this ability must be expressed as a verb, or action, to qualify as a capability. As an alternative, current joint doctrine similarly describes a critical capability as "a crucial enabler" for the center of gravity that is "essential" to mission accomplishment.[16]

Given the contextual framework of this thesis, what capabilities make the Department of Defense critical to national security? The 2011 *National Military Strategy* stated that the department must be capable of "fielding modular, adaptive, general purpose forces that can be employed in the full range of military operations."[17] Less than one year later in 2012, the Secretary of Defense released revised strategic guidance that focused on 10 capabilities, with special emphasis on four: counter terrorism, deter and defeat aggression, maintain a credible nuclear deterrent, and defend the homeland.[18] While both strategic documents hint at critical capabilities, those actions most essential to mission success are the department's ability to command and control its forces, project those forces, and if necessary, use its forces to protect the homeland. Without these general capabilities, the US military loses its

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[14] Strange, *Centers of Gravity & Critical Vulnerabilities*, ix.

[15] Strange, *Centers of Gravity & Critical Vulnerabilities*, x.

[16] Joint Publication 5-0, *Joint Operation Planning*, 11 August 2011, III-24.

[17] *National Military Strategy of the United States of America: Redefining America's Military Leadership*, 2011, 9, 18.

[18] *Sustaining US Global Leadership: Priorities for 21st Defense*, January 2012, 6. The 10 capabilities that the strategic guidance mentions are: countering terrorism through irregular warfare; deter and defeat aggression; project power despite anti-access/area denial challenges; counter weapons of mass destruction; operate effectively in cyberspace and space; maintain a safe, secure, and effective nuclear deterrent; defend the homeland and provide support to civil authorities; provide a stabilizing presence; conduct stability and counterinsurgency operations; and conduct humanitarian, disaster relief, and other operations.

ability to do almost any other mission, including defending the country and its territory against existential threats.

Critical Requirements

Dr. Strange defined his next link in the critical factors chain, critical requirements, as those "conditions, resources and means" essential for the center or gravity to operationalize critical capabilities.[19] Current joint doctrine mirrors his definition almost verbatim.[20] As each capability represents an action or verb, the associated requirement represents a noun. In the critical capabilities presented above—commanding and controlling forces, projecting forces, protecting the homeland—what does each require in order to accomplish the action? If each step in the process of projecting forces could be diagramed, for example, thousands of resources or means would arise as essential to putting effects on a target across the globe or "simply" deploying the requisite forces within the United States for disaster response. The 2011 *National Military Strategy* identifies space power as one such requirement because of its near ubiquity.[21] Taken in such a general sense, space power may apply across all domains and capabilities, but as Dr. Strange emphasized, context dictates the factors.[22] In the scenario of a major solar event, there exist some specific requirements that demand particular attention because of their susceptibility to space weather effects.

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[19] Strange, *Centers of Gravity & Critical Vulnerabilities*, ix.
[20] Joint Publication 1-02, *Department of Defense Dictionary of Military and Associated Terms*, 15 November 2012. Critical requirement - an essential condition, resource, and means for a critical capability to be fully operational.
[21] *National Military Strategy of the United States of America: Redefining America's Military Leadership*, 9, 18.
[22] Strange, *Centers of Gravity & Critical Vulnerabilities*, ix.

Critical Vulnerabilities

This chapter opened by listing three Department of Defense critical requirements that deserve special consideration: 1) space power; 2) electrical energy; and 3) US commercial capacity. By analyzing these requirements in the context of space weather, certain critical vulnerabilities to each of the above emerge. Defined as those "critical requirements, or components thereof, that are deficient, or vulnerable to neutralization or defeat in a way that will contribute to a center of gravity failing to achieve its critical capability," critical vulnerabilities can be thought of as an Achilles Heel.[23] Or put another way, an "aspect of a critical requirement which is deficient or vulnerable to direct or indirect attack that will create decisive or significant effects."[24]

While not the "collision of two living forces" that Clausewitz wrote about, space weather does "attack" the Defense Department's critical requirements in a metaphorical sense.[25] As shown through the historical examples in chapter two, various solar phenomena directly impact space-based systems and terrestrial power grids while indirectly impacting the commercial sector through its vital connection to the first two requirements of space and electricity. Specifically, for the Department of Defense, this translates into potential devastating impacts on its orbiting satellite networks, the North American bulk-power system, and eventually, the various commercial sectors such as banking, energy production, and manufacturing, that depend on either space, electricity, or in many instances, both. These represent the deduced vulnerabilities, distilled after the process of analysis—or as John Boyd coined it, the "destruction" of the center of gravity into its constituent elements to

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[23] Strange and Iron, *Understanding Centers Of Gravity and Critical Vulnerabilities*, 5-8. Besides the definition provided, Strange and Iron did suggest the connection with the ancient Greek hero, Achilles and his ill-fated heel; thus, the quote which opens this chapter.

[24] JP 1-02, *Department of Defense Dictionary of Military and Associated Terms*.

[25] Clausewitz, *On War*, 77.

expose the most vulnerable.[26] Each is susceptible to severe degradation or even catastrophic failure due to space weather, while at the same time absolutely critical for the Department of Defense to command and control its forces, project those forces to where they are needed, and lastly, conduct homeland defense. Using Dr. Jeff Reilly's model introduced earlier in the chapter (fig. 3) a critical factor analysis for US national security could flow as demonstrated below:

Table 1: Critical factor analysis of US national security in the context of a major space weather event

Center of Gravity US Department of Defense	**Critical Capability** 1) Command & Control forces 2) Project forces where needed 3) Defend the homeland
Critical Vulnerability 1) Space-based satellite networks 2) North American bulk-power system 3) Various commercial sectors that rely on space and electricity	**Critical Requirement** 1) Space power 2) Electrical energy 3) Commercial sector capacity

Source: Author's own work adapted from critical factor analysis model, figure 20 in Operational Design *by Dr. Jeff Reilly*[27]

Another run of the critical factor analysis model might yield different results in each cell; however, context must remain central to the process in order to achieve the results most applicable to the situation.

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[26] Boyd, "Destruction and Creation."
[27] Reilly, *Operational Design*, 43.

This harkens back to Clausewitz who advised that "one must keep the dominant characteristics of *both* belligerents in mind" (emphasis added) for out of the interaction between the two does a "certain center of gravity" develop.[28] In other words, just as Dr. Strange directed, context matters and there may be no more crucial contextual component than the direct interplay found amidst the two main entities

Summary

This chapter set about supporting the identification of the US Department of Defense as the most important component of the US national security enterprise. Using the center of gravity concept first developed by Carl von Clausewitz, it concluded that the Defense Department is that "on which everything depends" in the realm of national security.[29] It offered further support to the department as the center of gravity by showing how it dominates US national security in terms of size, budget, and combat power.

After acceptance of the center of gravity, the chapter turned to the express context of the thesis, space weather's impact on national security and specifically, the Department of Defense. Using Dr. Strange's "CG-CC-CR-CV" construct, it outlined a critical factor analysis of the Defense Department as the center of gravity. At each step of the analysis, the preceding findings were further broken down, ultimately resulting in three critical vulnerabilities that would prevent the department from carrying out core capabilities such as command and control of forces or projection of those forces. Table 1 graphically displayed the analytical process, starting at the center of gravity and progressing until culminating with the critical vulnerabilities. The next chapter explores these particular vulnerabilities in greater detail.

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[28] Clausewitz, *On War*, 595.
[29] Clausewitz, *On War*, 595-96.

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Chapter 4

The US Approach

With the establishment of the (Unified National Space Weather Capability), the (National Space Weather Program) Council has taken a bold step towards improving the Nation's space weather capabilities.[1]

Samuel P. Williamson,
Federal Coordinator for Meteorology, May 2013

Why the United States?

Several fundamental reasons exist why space weather and its impacts deserve special attention by the United States and its national security apparatus. Chapter three identified three Department of Defense critical requirements and their associated vulnerabilities—space-based satellite networks, the bulk-power system, and various commercial sectors. Left unmitigated, impacts upon these known weaknesses significantly raise the risk of failure in critical capabilities such as projecting forces or effects to hot-spots around the globe. This chapter addresses each of the vulnerabilities by first highlighting its necessity and then the specific impacts of space weather on the exposed weakness.

Space Power

Space power represents the first critical requirement of the Defense Department primarily because of the direct space weather impacts to the critical vulnerability, on-orbit satellite networks. Joint doctrine holistically defines space power as "the total strength of a nation's capabilities to conduct and influence activities to, in, through, and from

[1] S. P. Williamson and M. F. Bonadonna, "Unified National Space Weather Capability (UNSWC) Established," *Space Weather* (2013): 1-1.

space to achieve its objectives."[1] This description recognizes that space power has a broad constituency that goes well beyond the Department of Defense. As such, the President released the first-ever *National Space Policy of the United States of America* in 2010. The policy flatly states the use of and access to space constitutes a "vital" national interest that must be preserved.[2] The ensuing 2011 *National Security Space Strategy,* a Department of Defense document, echoes this point by declaring space as "*vital* to U.S. national security" (emphasis added).[3]

Both statements support the overarching 2010 *National Security Strategy* which asserts that US "space capabilities underpin global commerce" and "bolster [US] national strengths" and those of its allies.[4] US space power thus offers direct support to two of the four "enduring national interests" outlined in the *National Security Strategy*—security and prosperity—while indirectly supporting a third, international order, mostly through the prestige the United States derives from its demonstrated prowess in space.[5] To those ends, the United States has committed itself to maintaining leadership in the domain and further developing its space power.

The Department of Defense, in particular, did its part to bolster US space power by budgeting over $43 billion for space related activities in 2010.[6] This total represented nearly 70 percent of the entire US government space budget that year.[7] If the Defense Department's space

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[1] JP 1-02, *Department of Defense Dictionary of Military and Associated Terms*.
[2] *National Space Policy of the United States of America*, 28 June 2010, 14.
[3] *National Security Space Strategy: Unclassified Summary*, January 2011, 14.
[4] *National Security Strategy of the United States of America*, May 2010, 52.
[5] *National Security Strategy of the United States of America*, 52. Robert Gilpin, *War & Change in World Politics* (Cambridge: Cambridge University Press, 1981), 30-34.
[6] "The Space Report 2011," The Space Foundation, in Neil deGrasse Tyson, *Space Chronicles: Facing the Ultimate Frontier*, ed. Avis Lang (New York: W.W. Norton, 2012), 337. $43 billion is the combination of the space budget estimates for the Department of Defense, National Reconnaissance Office, and the National Geospatial-Intelligence Agency. The latter two organizations are actually combat support agencies subordinate to the Defense Department and thus their budgets should be included with their parent organization.
[7] "The Space Report 2011," The Space Foundation, in Tyson, *Space Chronicles*, 337.

budget were compared to the 2010 budgets of non-US governments, it would be nearly 10 times greater than the closest competitor, the European Space Agency, and over 11 times greater than the closest individual country, Japan.[8] With this unmatched purchasing power, the department has fielded an impressive fleet of satellites that enable all three of the aforementioned critical capabilities.

Due to their significant susceptibility to space weather, these on-orbit satellite networks and the signals they transmit represent a critical vulnerability to the Department of Defense. Examples of the constellations include the global positioning system used for navigation, the wideband global satellite communications system used for secure links in multiple frequencies, the space-based infrared system used for early warning missile detection, the advanced extremely high frequency used for jam resistant strategic communications, and the defense meteorological satellite program used for global weather imaging.[9] Although positioned in various orbits from geostationary to polar, the different space weather phenomena can still affect each type, even those hardened against radiation. Impacts include single-event upsets to the satellite's processor, increased atmospheric drag that places the satellite in a suboptimal or degrading orbit, and potentially catastrophic failure if the satellite loses contact with its ground stations due to loss of orientation. Moreover, solar interaction with the Earth's atmosphere can disrupt or distort the satellite signals, rendering the satellite mission ineffective. Space weather threatens more than just US space capabilities, however—there exists a second, equally exposed, but terrestrial risk to US national security.

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[8] "The Space Report 2011," The Space Foundation, in Tyson, *Space Chronicles*, 377-78.
[9] "US Air Force Factsheets," US Air Force, http://www.af.mil/information/factsheets/index.asp (accessed 28 May 2013). Referenced factsheets for Wideband Global SATCOM (WGS) system. "USAF Almanac 2013," *Air Force Magazine*, May 2013, 104-05. Referenced entry on Advanced Extremely High Frequency (AEHF) satellite system.

Electrical Power

Unlike the direct effects to Defense Department space-based assets, space weather impacts to the electrical power supply affect the department indirectly. The power grid itself, a non-government entity, would take the brunt of terrestrial impacts from a geomagnetic storm. For this reason, when addressing space weather impacts to the department, most neglect the potentially catastrophic connection to electrical power, the second critical requirement of the department. Moreover, the US power grid is generally assumed to be reliable because it continues to function day in and day out.[10] In a worst case scenario, when an outage happens as a result of a natural disaster such as a hurricane, utility companies band together to usually restore power within weeks. If the outage happens to persist longer, evacuees can generally shelter at locations with power found within a few hundred miles. The effects of a major solar storm on large portions of power grid, however, would be unprecedented and as such, it represents a critical vulnerability to the department's requirement for electrical power.

The Department of Defense requires an enormous amount of electrical power to carry out its day-to-day missions. For 2006, and just at fixed installations within the United States, the department consumed 3.8 billion kilowatt hours of electricity.[11] That same year the United States as a whole consumed 3,817 billion kilowatt hours, resulting in a 0.01 percent share for the department.[12] This may not appear to be a significant amount but when compared against similar end-users (as opposed to total residential use, for example), that percentage jumped to 0.3 percent of all electricity consumed for public purposes.[13]

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[10] Defense Science Board Task Force, *More Fight – Less Fuel.* (Washington, DC: 2008), 53.
[11] Defense Science Board Task Force, *More Fight – Less Fuel.* 11.
[12] B. T. Fichman, "April 2013 Monthly Energy Review," ed. Office of Energy Statistics (Washington, DC: US Energy Information Administration, 2013), 93.
[13] Fichman, "Monthly Energy Review," 109.

This heavy use of electricity does not in itself represent a weakness. Rather, the vulnerability exists from the Defense Department's almost exclusive reliance on the North American bulk-power system, defined as the "facilities and control systems necessary for operating an interconnected electric energy transmission network."[14] Basically, the system covers all network-to-network and long-line transmission, while excluding local distribution. The department receives 99 percent of its electricity through this bulk-power system that lies "outside the fence."[15] Accordingly, that electricity travels mostly over infrastructure the department does not control—approximately 85 percent is commercially owned and operated.[16]

The specific weakness lies in the extra-high voltage transmission component of the bulk-power system. This element of the wider system, energized at a higher voltage and lower resistance, allows for the wide distribution of electricity over "more than 200,000 miles of high-voltage transmission lines."[17] Utility companies designed and constructed almost the entire network before the 1989 cascading event in Quebec led to a better grasp of the effects of caused by space weather.[18] Now they understand that geomagnetic storming caused by a coronal mass ejection can result in significant disturbances of the Earth's geomagnetic field as described in chapter two.[19] Just like a motor, the fluctuating magnetic field induces a current which can travel through the ground or

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[14] *Electric Reliability,* US Code title 16, sec. 824o (2011).
[15] Defense Science Board Task Force, *More Fight – Less Fuel.* 18. The report cites the Naval Surface Warfare Center—Dahlgren in providing this oft-quoted statistic in a briefing delivered to the task force on 6 September 2006. This percentage was confirmed to the author in a 19 May 2013 e-mail exchange with Dr. James Galvin, the energy and water program manager for the Office of the Secretary of Defense Strategic Environmental Research and Development Program (SERDP)/Environmental Security Technology Certification Program (ESTCP).
[16] Defense Science Board Task Force, *More Fight – Less Fuel.* 18.
[17] "Electricity Transmission," Edison Electric Institute, http://www.eei.org/ourissues/ElectricityTransmission/Pages/default.aspx (accessed 26 May 2013).
[18] "Geomagnetic Disturbance (GMD) Background," ed. North American Electric Reliability Corporation (Princeton, NJ: NERC, 2011), 1.
[19] "Geomagnetic Disturbance (GMD) Background," 1.

should one be available, another path of lower resistance. If this geomagnetically induced current takes the extra-high voltage transmission lines because of their relatively low resistance, it could saturate the high voltage transformers stationed throughout the network, damaging them beyond repair.[20] Damage to enough transformers would likely lead to cascading failures over wide areas of North America.

A 2010 study commissioned by the Department of Energy examined geomagnetic storms of various strengths and their impact on the bulk-power system. The study found that a storm on par with the 1921 great geomagnetic storm, estimated to occur about once every one hundred years, would likely knock out electric power distribution to wide swaths of the Northeast United States, Mid-Atlantic, Ohio Valley, and Pacific North West.[21] Given an image with the area affected, the National Academy of Sciences estimated it would directly impact over 130 million Americans, or over 42 percent of the 2010 census population.[22] Certainly, many US military bases in the affected areas, including the national capital region, would lose power supplied by the bulk-power system. Moreover, given the permanent damage to the system, estimates for full restoration of the network range from just a few months to several years.[23] Hundreds of foreign-made high voltage transformers would need replacement, each engineered to the unique factors present in its particular placement.[24]

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20 "Geomagnetic Disturbance (GMD) Background," 1.

21 J. Kappenman, *Geomagnetic Storms and their Impacts on the US Power Grid*. (Goleta, CA: Metatech, 2010), 3-26.

22 Space Studies Board, *Severe Space Weather Events*. 78. Census figures taken from "USA QuickFacts," http://quickfacts.census.gov/qfd/states/00000.html (accessed 27 May 2013).

23 Space Studies Board, *Severe Space Weather Events*. 77-78.

24 Space Studies Board, *Severe Space Weather Events*. 77-78. The Kappenman study estimated between 368 and 1003 high voltage transformers are at risk for failure from geomagnetically induced currents (the range is a result of modeling two different thresholds). At the high end, the number of at-risk transformers represents over 50 percent of the network capacity (Tables 4-1 through 4-3).

While the 1989 event did raise awareness to the hazards of space weather within the electrical power industry, the situation may have actually regressed since then. A recent National Academy of Sciences report outlined an increasingly vulnerable US power network due to extraordinary stress on the transmission system from two principal sources: 1) languishing upgrades to infrastructure and 2) unprecedented demand from continual large-volume power trading.[25] Even if plant operators have learned valuable lessons from the previous space weather events, if their equipment remains largely susceptible to strong geomagnetically induced currents, for example, there is only so much they can do to try and stave off the effects. On the other hand, a "near-simultaneous, correlated, multipoint" failure in the power grid, the kind likely to be experienced with a severe space weather event, would allow "little or no time for meaningful human interventions."[26] Thus, given the current state of North America's bulk-power system and the likelihood of its collapse when, not if, a major space weather event strikes the Earth, this represents a critical vulnerability for the Department of Defense.

The Commercial Sector

The commercial vulnerability consists of the cumulative impact to all those sectors that depend on space and electricity to conduct business. Examples of this third critical requirement include the banking, financial, energy production, transportation, manufacturing, healthcare, and utility sectors, to name just some of the most important. The Department of Defense depends on these commercial sectors in order to conduct routine business as well as maintain readiness for numerous contingencies. In addition, it needs the manufacturing sector

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[25] Committee on Enhancing the Robustness and Resilience of Future Electrical Transmission and Distribution in the United States to Terrorist Attack, *Terrorism and the Electric Power Delivery System* (Washington, DC: The National Academies Press, 2012), 8.
[26] Kappenman, *Geomagnetic Storms and their Impacts on the US Power Grid*. 1-31.

to provide the myriad supplies and weapons required to fulfill operations plans. Equally important, the department's several million employees and their families rely on these sectors to meet basic needs like clean water, food, emergency medical care, and fuel for their vehicles. For these reasons and more, the various commercial sectors susceptible to direct or indirect impacts from space weather create a critical vulnerability for the Department of Defense.

Given the importance of both space and electrical power to the United States as a whole, the government identified assets in each system as "critical infrastructure." A recently issued executive order from the President defined critical infrastructure as that which is "so *vital* to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters" (emphasis added).[27] As such, US policy mandates resiliency in critical infrastructure, described as "the ability to adapt to changing conditions and prepare for, withstand, and rapidly recover from disruption."[28]

At least for space, the Department of Defense further declared that it will seek resiliency to enable operations in adverse space conditions, perhaps in recognition that not all threats emanate from an enemy.[29] The US power grid, however, sits outside Defense Departmental authority and so to a certain extent, it must rely on other governmental agencies to raise awareness with the commercial domain. To that end, the Federal Emergency Management Agency hosted international and electric industry partners at a 2010 table-top exercise that explored how a powerful, but not extreme, geomagnetic storm would affect power grids in the trans-Atlantic. With the North American bulk-power system

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[27] Executive Order 13636, *Improving Critical Infrastructure Cybersecurity*, 12 February 2013, 11739. Emphasis added to the word "vital."
[28] *National Security Strategy of the United States of America*, 52.
[29] *FACT SHEET: Resilience of Space Capabilities*, January 2011.

impacted for an estimated six-months, the participants produced several recommendations designed to boost the resiliency of grid.[30] In spite of this, and as is often the case with many promulgated lessons about space weather, the electric industry has complete discretion on which recommendations to adopt and when to adopt them. Thus, more vigorous action is needed.

Vital Interest

While it behooves governments and scientists worldwide to maintain vigilance over the Sun, the burden of monitoring solar weather falls justifiably on the more technologically advanced space-faring states. Among the handful of these nations, the United States stands apart due to the combination of its scientific, commercial, and defense-related endeavors in space. By declaring continued access to and use of space as a "vital" national interest, the United States communicates a powerful message both internally and externally. For the phrase "vital interest" holds special meaning, especially when used by the President as in the case of the aforementioned policy documents. Martin Wight defines it as that which "a power deems essential to its continued independence" and "it will go to war to defend."[31] The United States will not engage the Sun in conflict anytime soon, but if both space assets and the bulk-power system, as critical infrastructure, deserve the "vital" modifier, space weather merits more than just observation and study. Addressing space weather requires a guiding policy that mitigates impacts from all but the most extreme events.[32]

Primary US Stakeholders

With arguably the most at risk given its world-leading economy, robust space program, and high technological base, in 1994 the United

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30 *Managing Critical Disasters in the Transatlantic Domain--The Case of a Geomagnetic Storm: Workshop Summary*. (Boulder, CO: FEMA, 2010).

31 M. Wight, *Power Politics*, ed. H. Bull and C. Holbrand (New York: Holmes & Meier Publishers, Inc., 1978), 95.

32 Richard Rumelt, *Good Strategy, Bad Strategy: The Difference and Why It Matters* (New York: Crown Business, 2011), 84-85.

States instituted a broad interagency agenda to meet the needs of the many stakeholders across America's public and private sector.[33] Called the National Space Weather Program, its managing council offers a vehicle for government, industry, and academia to address the needs of the entire community in a unified manner.[34] Currently the council brings representatives together from seven cabinet level departments and two federal agencies to provide strategic leadership and coordinated vision to the nation's space weather enterprise. Operationally, the program focuses on monitoring and characterizing the space environment in order to provide adequate warning of impending hazards.

To that end, the National Space Weather Program coordinates and deconflicts the applicable activities of the Department of Commerce, National Aeronautics and Space Administration, and Department of Defense.[35] Together these three agencies contribute the most significant elements of the space weather infrastructure that ensures uninterrupted observation of the Sun and near-Earth environment.[36] Each leg of this space weather triad delivers critical capabilities necessary to meet not only organic requirements from a significant constituency that depends on timely, accurate warnings and forecasts, but also the needs of the nation.

Nested under the Department of Commerce, National Oceanic and Atmospheric Administration, and National Weather Service, the Space Weather Prediction Center serves government, industry, and the general public as the primary producer and disseminator of space weather products.[37] In line with its parent organizations, the center seeks to

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[33] Richard Fisher, "National Space Weather Program," National Aeronautics and Space Administration, http://www.nswp.gov/nswp_index.htm (accessed 18 October 2012).
[34] Fisher, "National Space Weather Program," http://www.nswp.gov/nswp_index.htm (accessed 18 October 2012).
[35] Space Studies Board, *Severe Space Weather Events*. 4.
[36] Space Studies Board, *Severe Space Weather Events*. 3-4.
[37] "Space Weather Prediction Center," http://www.swpc.noaa.gov/AboutUs/index.html (accessed 27 January 2013).

minimize disruption and damage to America's commercial infrastructure, yet its vision of "a nation prepared to mitigate the effects of space weather" leads it to provide an informative educational program to the American public.[38]

The National Aeronautics and Space Administration, as the only government agency that currently has personnel living in the space environment, needs to protect its dedicated astronaut corps and their on-orbit home, the *International Space Station*. To accomplish this, the agency contributes solar images from a constellation of very sophisticated satellites positioned to continually monitor the whole sun from different perspectives using multiple electro-optical sensors (see figure 4 on following page).[39] Using their satellites and Space Weather Prediction Center forecasts, the agency's various mission control centers regulate activities aboard spacecraft and in the case of mission control in Houston, stand ready to trigger an alarm that would initiate rapid safety protocols for astronauts both inside and outside of the space station.

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[38] "Space Weather Prediction Center," http://www.swpc.noaa.gov/AboutUs/index.html (accessed 27 January 2013).

[39] J. Gurman, "Solar TErrestrial RElations Observatory: 3-D View of the Sun and Heliosphere," National Aeronautics and Space Administration, http://stereo.gsfc.nasa.gov/ (accessed 23 February 2013).

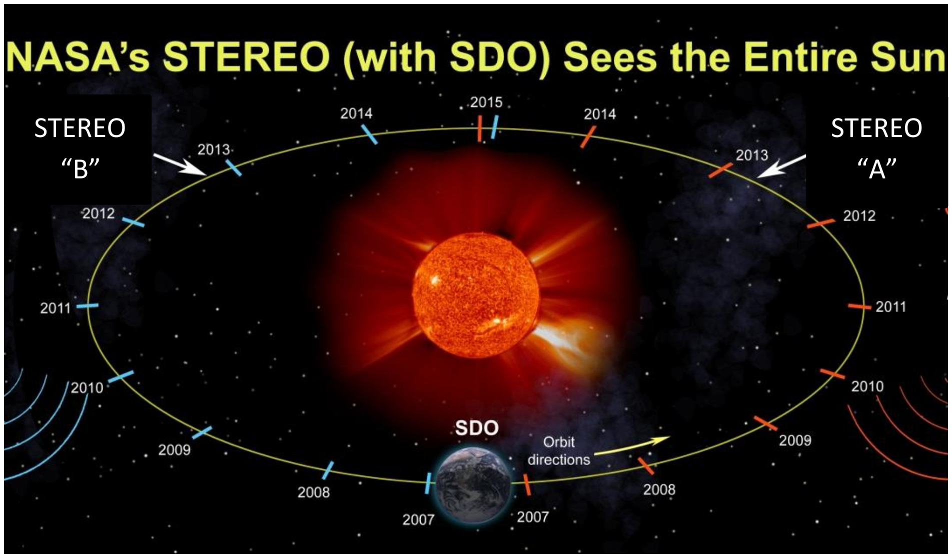

Figure 4: NASA's sun monitoring constellation consisting of twin STEREO (A & B) satellites and the Solar Dynamics Observatory (SDO)
Source: http://stereo.gsfc.nasa.gov

Although a close collaborator with the Space Weather Prediction Center, the Department of Defense has special and sometimes unique national security requirements that necessitate an organic space weather capability. All the military services and defense agencies depend heavily on space-based assets to fulfill strategic and operational requirements, leaving them especially vulnerable to disruptions in times of conflict.[40] Moreover, space weather has the potential to affect many missions in all domains due to its impacts on the atmosphere and electromagnetic spectrum.[41] Within the department, the Chairman of the Joint Chiefs delegated to the Air Force sole responsibility for "space environmental operations in support of all elements."[42] With that mission, the Air Force Weather Agency at Offutt Air Force Base, Nebraska, conducts space weather prediction and hazard identification by operationalizing data from its worldwide network of solar observatories as well as other

[40] *National Security Space Strategy: Unclassified Summary*, 14.
[41] Air Force Doctrine Document 3-59, *Weather Operations*, 27 August 2012, 10-12.
[42] Chairman of the Joint Chiefs of Staff Instruction 3810.01C, *Meteorological and Oceanographic Operations*, 18 September 2009, B-3.

interagency products.[43] Essentially, through a finer understanding of military missions and systems, the agency Airmen can tailor their space weather forecasts and advisories to the needs of joint operators in all domains.

Lastly, other partners on the national council include the Departments of State and Energy, the Federal Emergency Management Agency from the Department of Homeland Security, the United States Geological Survey from the Department of Interior, the Federal Aviation Administration from the Department of Transportation, and the National Science Foundation.[44] Altogether, the interagency program safeguards many trillions of dollars of infrastructure and commerce, the health and well-being of astronauts, and the national security of the United States.

Figure 5: National Space Weather Program participants

Source: Unified National Space Weather Portal found at http://www.swpc.noaa.gov/portal/

Summary

The Department of Defense has an undeniable security interest in mitigating space weather impacts to three critical vulnerabilities: its space-based satellite networks, the North American bulk-power system, and the various commercial sectors that in a similar way are dependent upon space and electrical power. An extreme space weather event as depicted in chapter two will affect nearly all sectors of American society

[43] "2nd Weather Squadron, Space Weather Flight," 55th Wing Public Affairs, http://www.afweather.af.mil/library/factsheets (accessed 18 October 2012).
[44] Fisher, "National Space Weather Program," http://www.nswp.gov/nswp_index.htm (accessed 18 October 2012).

and thus the interagency National Space Weather Program provides a much needed forum for coordination and cooperation among federal government departments and agencies. Given that space weather impacts do not discriminate based on nationality, efforts to partner with close allies and others with a vested interest offer additional venues for burden sharing in an increasingly tight budget regime. With this demonstrated need and vulnerability, the next chapter will put forth a "guiding policy," the second element of the strategy kernel.[45]

[45] Rumelt, *Good Strategy, Bad Strategy*, 77.

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Chapter 5

Conclusion

> *Coordination and cooperation toward objectives, even if the participants are not necessarily part of the same command or organization—the product of successful unified action.*
>
> Unity of Effort, from Joint Publication 1

Having sufficiently diagnosed the challenge of space weather in the preceding chapters, the following problem statements focus attention on the most crucial aspects for further development.[1]

1) Impacts from space weather threaten US national security, and specifically place the Department of Defense at significant risk of executing critical capabilities.
2) Of even more significance, an Earth-bound major or extreme space weather event on par with historical examples represents an existential threat to the twenty-first century American way of life.

Given this context, the United States government should adopt an overall guiding policy that informs coherent actions to address the space weather challenge and mitigate its impacts.

Guiding Policy

In order to effectively deal with the challenge as presented above, it should be policy of the United States to consider space weather an issue of national security that requires concrete mitigation measures to lessen the risks it presents. Currently, those outside the space weather

[1] Rumelt, *Good Strategy, Bad Strategy*, chap. 5. In chapter five, Rumelt first outlines then details the three elements of his strategy kernel, first introduced in chapter one of this paper. Those elements—diagnosis, guiding policy, coherent actions—as applied to the thesis, will be revisited throughout this chapter.

community who do not fully appreciate its potential impacts may treat space weather as any other phenomenon that can lead to a natural disaster. Analogous scenarios might include a hurricane making landfall on a heavily populated coast or a strong, shallow earthquake striking beneath a large city. Specific US examples abound—names like Katrina, Sandy, Northridge, or San Andreas immediately come to mind.

These and other natural disasters can cause incredible devastation and suffering in the areas where they strike. They pale, however, next to the probable reach of an extreme geomagnetic storm. Impacts would be felt around the world, with wide swaths of North America potentially losing basic services for months, if not longer.[1] Upwards of 40 percent of the US population could be forced to try and make do without power.[2] The United States has never faced a rapid disaster of such magnitude, especially to a population acclimated to the comforts of twenty-first century life.

As an extreme space weather event that strikes the Earth is not like a normal natural disaster with relatively limited impacts, it necessitates greater attention and focus, coupled with prudent action, in order to adequately address the risk. The White House Office of Science and Technology, Subcommittee on Disaster Reduction, produced a 2010 report on space weather that listed a "variety of hazards" as well as some rather innocuous impacts.[3] While the "implementation plan" described space weather effects as "global in nature," and the subcommittee deserved much credit for tackling the issue, the report was just one of more than a dozen in the series that addressed typical natural disasters.[4] Thinking about this particular issue requires one to consider the wider and longer lasting implications, including the catastrophic impacts likely

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1 Kappenman, *Geomagnetic Storms and their Impacts on the US Power Grid*. 3-1.
2 Space Studies Board, *Severe Space Weather Events*. 78.
3 *Space Weather*. Grand Challenges for Disaster Reduction Implementation Plan. (Washington, DC: Subcommittee on Disaster Reduction, 2010), 2.
4 *Space Weather*. 2.

to result from an extreme event that may not be all that far off. As detailed in chapter two, Dr. Pete Reilly estimated an approximately 12 percent chance for a Carrington-type event within the 10 years starting summer 2011.[5] By elevating space weather to the level of national security and requiring concrete mitigation measure, greater authority would be available to implement the following set of recommended coherent actions in support of this policy.

Coherent Actions

According to Rumelt, coherent actions consist of coordinated steps that "work together in accomplishing the guiding policy."[6] Producing coordinated effort goes to the very core of the first recommended action:

1. Establish an interagency task force with the requisite authority to coordinate and unify space weather mitigation efforts within the federal government.

Establishment of this task force recognizes and builds upon the highly successful interagency National Space Weather Program and its council described in the previous chapter. Chaired by the federal coordinator for meteorological services, the council has "taken a bold step towards improving the Nation's [*sic*] space weather capabilities" in the recent ratification of the unified national space weather capability memorandum of understanding.[7] The memorandum enables an even stronger partnership among participating agencies as they seek to implement the program's strategic plan.[8]

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5 Riley, "On the probability of occurrence of extreme space weather events," 1-12.
6 Rumelt, *Good Strategy, Bad Strategy*, 77.
7 Williamson and Bonadonna, "Unified National Space Weather Capability (UNSWC) Established," 1-1. The news of the council acceptance of the MOU was first published 22 May 2013.
8 Williamson and Bonadonna, "Unified National Space Weather Capability (UNSWC) Established," 1-1.

The task force would not only preserve those agreements already in place, but serve to strengthen them with newly instilled authority. For instance, the program basically began as a voluntary group that joined an already existing committee with poor attendance.[9] Even now, agencies outside the core group are under no compulsion to send a representative, much less one with sufficient license to effect any necessary change within their originating organization. The task force, headed by a deputy on the National Security Staff, would have the influence within the Executive Branch to ensure motivated participation. In addition, with leadership from the Executive Office of the President, the task force would potentially garner more attention from entities outside the government, which leads to the second recommended action:

2. Create wider forum, with the task force at its core, which encourages full participation of international partners, academia, various commercial sectors, think tanks, media, etc.

Joint doctrine has a concept called unified action that is designed to achieve unity of effort between the US joint force and the many organizations outside the American military found in modern conflict zones.[10] This same idea, transferred to the space weather task force, would provide US leadership and direction to an area where America has the most risk. By delineating the task force's responsibility for strictly federal-related issues, yet creating a venue where they can tap into a wider group with different experiences and knowledge, the task force stands to gain. Some will resist a new bureaucratic organization, especially one that invites non-American participation. Before dismissing the task force or wider unifying forum, however, consider the

[9] R. M. Robinson and R. A. Behnke, *The U.S. National Space Weather Program: A Retrospective*, ed. P. Song, H. J. Singer, and G. L. Siscoe, Online ed., Space Weather (Washington, DC: American Geophysical Union, 2001).
[10] Joint Publication 3-0, *Joint Operations*, 11 August 2011, I-8,9.

organization that will emerge after space weather effects begin having major impacts on national security. Better to establish the task force now and put it to work mitigating the impacts as it can. The task force could have an important role in coherent action number three:

3. Pass into law an amendment to the Federal Power Act that mandates greater protection to the bulk-power system against geomagnetic disturbances.

In 2010, the US House of Representatives approved the "Grid Reliability and Infrastructure Defense Act," designed to strengthen the bulk-power system against cyber-attacks, electromagnetic pulses, and solar induced geomagnetic storms.[11] The 9 June House Congressional Record shows the bi-partisan bill passed *unopposed* through committee and was sent to the Senate by voice vote where it died in committee.[12] In the 112th Congress, an almost verbatim bill, the SHIELD Act, stripped of any controversial cybersecurity measures, didn't even make it out of committee.

Both bills would have required the Federal Energy Regulatory Commission to take directive measures to ensure industry safeguarded electric infrastructure that served critical defense facilities, as identified by the President.[13] Again, each would have not only protected against space weather, but also the electromagnetic pulse given off by a nuclear detonation and intentionally induced geomagnetic disturbances.[14] Besides the specific attention given to the Department of Defense, in presenting support to passage of the "Grid Reliability and Infrastructure Defense Act," one Representative recognized that "a modern society is

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[11] House, *Grid Reliability and Infrastructure Defense Act*, 111th Cong., 2d sess., 2010, HR 5026.
[12] House, *Congressional Record for 9 June 2010*, 111th Cong., 2d sess., 2010. H4258-H4262.
[13] House, *GRID Act*.
[14] House, *Congressional Record for 9 June 2010*.

characterized by the presence of three things: clean available water, properly functioning sewage and sanitation services, and electricity," all of which could not be possible in America today without the bulk-power system.[15]

Although strong laws that specifically address critical vulnerabilities would lead to faster installation of mitigation measures, the Federal Energy Regulatory Commission has continued to work a long review process with the electrical industry that just recently resulted in the issuing of new mandatory reliability standards in the Code of Federal Regulations. The additions directly "address the impact of geomagnetic disturbances (GMD) on the reliable operation of the Bulk-Power System [*sic*]."[16] While much slower than writing the standards into a bill that becomes law, the requirement for standards bodes well for the overall health of the power grid.

The three coherent actions outlined above represent but a few of the many coordinated steps that could be taken to carry out the guiding policy of space weather as an issue of national security requiring concrete mitigation measures. Ideally, the Department of Defense would embrace this elevation and implement its own actions in line with the policy. For example, the department has over 440,000 structures on 4,451 military sites within the United States.[17] As cited before, 99% of the electrical power to these sites travels through the bulk-power system.[18] By expanding the use of local "microgrids" fed by renewable sources like wind or solar, interruptions to the commercial power supply

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[15] House, *Congressional Record for 9 June 2010*. H4262. Quote taken from House floor testimony of Representative Yvette Clarke of Brooklyn, New York.

[16] *Reliability Standards for Geomagnetic Disturbances, US Code*, title CFR 18, sec. Part 40 (2013). The final rule was issued by the FERC on 16 May 2013 and was scheduled to take effect on 22 July 2013, 60 days after publishing in the Federal Register (23 May 2013). As cited in, "Reliability Standards for Geomagnetic Disturbances," *Federal Register* 78, no. 100 (2013): 30747.

[17] *Base Structure Report Fiscal Year 2012 Baseline: A Summary of DOD's Real Property Inventory*. (Washington, DC: DoD, 2012).

[18] Defense Science Board Task Force, *More Fight – Less Fuel*. 18.

could theoretically be managed indefinitely.[19] Priority for such systems would be given to so-called "defense critical assets," those facilities "of such extraordinary importance to DOD operations in peace, crisis, and war that their incapacitation or destruction would have serious, debilitating effect on the ability of DOD to fulfill its missions."[20] These assets undoubtedly already have generator backup, but given the potential that large sections of the bulk-power system could be off-line for a year or more from unavailability of transformers, the backup power source may be useless when the fuels sector has stopped producing and the remaining fuel supply runs dry. Again, more prospective actions that support the guiding policy should be considered, but with those already listed above, all elements of the strategy kernel are present. A review of the entire kernel will now serve as a thesis summary before concluding.

The Strategy Kernel

Introduced in chapter one, Rumelt's strategy kernel ensures a sound basic structure to strategy formulation.[21] The first element, diagnosis of the challenge at hand, required research into, and an historical survey of, space weather, its origins, and impacts. By applying Clausewitz's *Schwerpunkt* to US national security, the Department of Defense arose as the center of gravity and thus stripped away extraneous content, an important feature of diagnosis.[22] A critical factors analysis, outlined in chapter three, further scoped the challenge down to space weather's impact on three critical vulnerabilities of the department. With the diagnosis of "what" answered, the more crucial question of "why" was explored in chapter four, as well as brief rendering of the current "how" through the National Space Weather Program.

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[19] S. B. Van Broekhoven et al., *Microgrid Study: Energy Security for DOD Installations*. (Lexington, MA: MIT, 2012).
[20] GAO-09-740R Defense Infrastructure, *Defense Critical Infrastructure: Actions Needed to Improve the Consistency, Reliability, and Usefulness of DOD's Tier 1 Task Critical Asset List*, 17 July 2009, 1-2.
[21] Rumelt, *Good Strategy, Bad Strategy*, 77.
[22] Rumelt, *Good Strategy, Bad Strategy*, 79-80.

This concluding chapter opened with a distilling of the diagnosis down into dual problem statements before establishing a new guiding policy the US in the realm of space weather. Since space weather represents a grave threat to US national security and even an existential threat to the American way of life, it should be an issue of national security and require mitigation of impacts identified critical vulnerabilities. Having completed the first two elements, context was set for coherent actions to supported policy. Three national level actions, each coordinated to build upon the others for synergistic effect, would make significant headway to achieving the stated policy. An additional step, widespread adoption of microgrids at military installations, demonstrated how actions at the department level serve to fulfill the policy while maintaining coherence with higher actions.

Conclusion

America, its national security, and the Department of Defense are vulnerable. With an inability to accurately predict major solar activity far in advance, an extreme solar event could erupt from the Sun with little warning and catastrophically alter America as it is known today. If that happened, the Defense Department would suffer an almost unimaginable loss in capability. Significant risk to the department still exists from much less powerful events that could impact its space-based infrastructure and even the terrestrial power grid. Given this ever-present and increasing risk, the United States must pursue a policy that raises general awareness and focus, while at the same time mitigates the impacts to vulnerabilities.

This thesis seeks to raise awareness of space weather and its impacts, while also recommending specific actions that policy makers might adopt to help the country address the issue. The country will inevitably make substantial advances in technology over the next decade and more. As that happens, Americans will continue to become increasingly dependent on those advancements, resulting in a greater

and greater societal impact should that technology become disabled and other means of provision are lost to history. With the current solar cycle already in its peak phase, the deadline lies ahead with the next projected solar maximum in 11 years. The strategy enclosed herein will sow the seeds that might just reap untold benefits for the United States and its security—that target is set for 2024.

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